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THE JOURNAL OF
The Institution of Electrical Engineers

ORIGINALLY
The Society of Telegraph Engineers
FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

EDITED BY W. K. BRASHER, SECRETARY
SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2.

Telegrams: "VOLTAMPERE, PHONE, LONDON." Telephone: TEMPLE BAR 7676.

Vol. 87 AUGUST, 1940 No. 524

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E. and F. N. SPON LIMITED, 57 HAYMARKET, LONDON, S.W.1.
CHEMICAL PUBLISHING COMPANY OF N.Y. INC., 148 LAFAYETTE STREET, NEW YORK.

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[*Continued on page (III) of Cover.*

APPLICATIONS AND LIMITATIONS OF THE INVERSE-TIME OVERLOAD RELAY TO THE PROTECTION OF AN 11-kV NETWORK

By J. W. GALLOP, B.Sc.(Eng.), Associate Member,* and R. H. BOUSFIELD, B.Sc.(Eng.), Graduate.*

(*Paper first received* 22*nd March, and in revised form* 26*th April*, 1939; *read before the* NORTH-WESTERN CENTRE 23*rd January, and before the* NORTH MIDLAND CENTRE 27*th January*, 1940. *The paper would also have been read and discussed before the* TRANSMISSION SECTION *on the* 13*th December*, 1939, *but the meeting was cancelled owing to the war.*)

SUMMARY

Methods of grading overload inverse-time relays, with definite minimum time, on an 11-kV system are discussed with special reference to the reduction of tripping times throughout, especially at the source of supply. A method is developed which attains this object and allows a large number of relays to be used in series. A system of recording network short-circuit calculations and emergency relay settings is also discussed.

INTRODUCTION

The overload relay for high-voltage feeder protection is rapidly giving place to relays whose action depends upon the unhealthy state of the system and not upon the magnitude of the fault current. The overload relay cannot, however, often be dispensed with, and it is widely used as a back-up relay. A knowledge of the correct use and setting of these relays is therefore still necessary, even in cases where other methods of feeder protection are employed.

It is a fundamental of any protective system that it shuts down the minimum of plant and as quickly as possible. This applies to any system, even although it may be backing up another which normally gives superior performance. The authors feel that there is a growing tendency to lose sight of the potentialities of overload protection, owing to the superior performance of other systems, and to install additional protection where, in some cases, it is unnecessary.

FAULT CURRENTS

The overload relay depends for its action on the magnitude of the fault currents. It is necessary to have a knowledge of the value and distribution of these fault currents in the network if the grading is to be carried out with confidence. It will be shown that the maximum possible fault current, at any point in the network, determines the values of relay settings to ensure discrimination under all fault conditions. It is not proposed to discuss the calculation of fault currents in detail, but it should be realized that, for a 3-phase system with a solidly-earthed star point, the value of the phase-to-earth fault gives the maximum value of fault current. When a system is earthed through a resistor, the current for a 3-phase fault is often the maximum possible. It is not advisable to neglect resistance in these calculations, as in many cases it is the deciding factor in determining the fault current.

In the examples quoted later the current for a 3-phase fault is the greater.

CALCULATION OF RELAY OPERATING TIME

The relay in its usual form has two controls, a current plug setting (P_m), and a time-setting multiplier (T_m). The current plug settings usually range from 50 % to 200 % in steps of 25 %, except on earth-leakage relays, where lower settings are used. The time multiplier ranges from 0 to 1·0 in steps of 0·05. The current plug setting alters the number of turns on the relay coils and hence alters the torque on the disc, if the relay is not saturated. If the relay is unsaturated the current plug affects the time of operation as well as the pick-up current. The plug setting (P_m) alters, in effect, the current-transformer ratio. Thus a 200/5 current transformer operating a relay with a plug setting (P_m) of 50 % is equivalent to a 100/5 current transformer operating the same relay with a plug setting of 100 %.

It is important to have a clear idea of the meaning of full-load current and pick-up current (i.e. the current at which the relay starts to move). A 5-amp. relay set at 100 % has a relay full-load current of 5 amp. and a pick-up current of, say, 1·3 times this, i.e. 6·5 amp. Similarly, at 200 %, the full-load current is 10 amp. and pick-up current 13 amp. This ensures stability at full-load current.

It is usual to give the relay characteristic curve as a time/plug-setting multiplier curve, where

$$\text{Plug-setting multiplier (P.S.M.)} = \frac{\text{Fault current in relay}}{\text{Relay full-load current}}$$

$$= \frac{\text{Fault current in primary of C.T.}}{\text{C.T. full load} \times \text{Plug setting \%}} \times 100$$

A typical time/P.S.M. curve is given in Fig. 1. It can be seen that at about 16 times full load the relay approaches its minimum time. A relay, connected to a 200/5 current transformer and set at 100 %, would have a full-load current on the primary side of 200 amp.; if set at 150 %, full-load current would be 300 amp. Thus, with a primary fault current of 1 000 amp. the P.S.M.'s would be 1 000/200 and 1 000/300 respectively. Clearly, if the fault current, plug setting, and current-transformer ratio are known, the P.S.M. can be found, and a time obtained from the time/P.S.M. curve.

The time setting (T_m) usually moves the initial position of the disc so that the length of travel to close the contacts is reduced. If a time/P.S.M. curve is available for a time setting of 1·0 it is necessary to multiply the results obtained from this curve by the time-setting multiplier used. This point is clearly shown in Fig. 1, which gives curves for time-setting multipliers of 1·0 and 0·5.

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* Bournemouth and Poole Electricity Supply Company, Ltd.

Thus to calculate the time of operation of a relay a knowledge of the following is necessary:—

(1) Time/P.S.M. curve for the relay.
(2) Current plug setting (P_m).
(3) Time setting (T_m).
(4) Fault current.
(5) Current-transformer ratio.

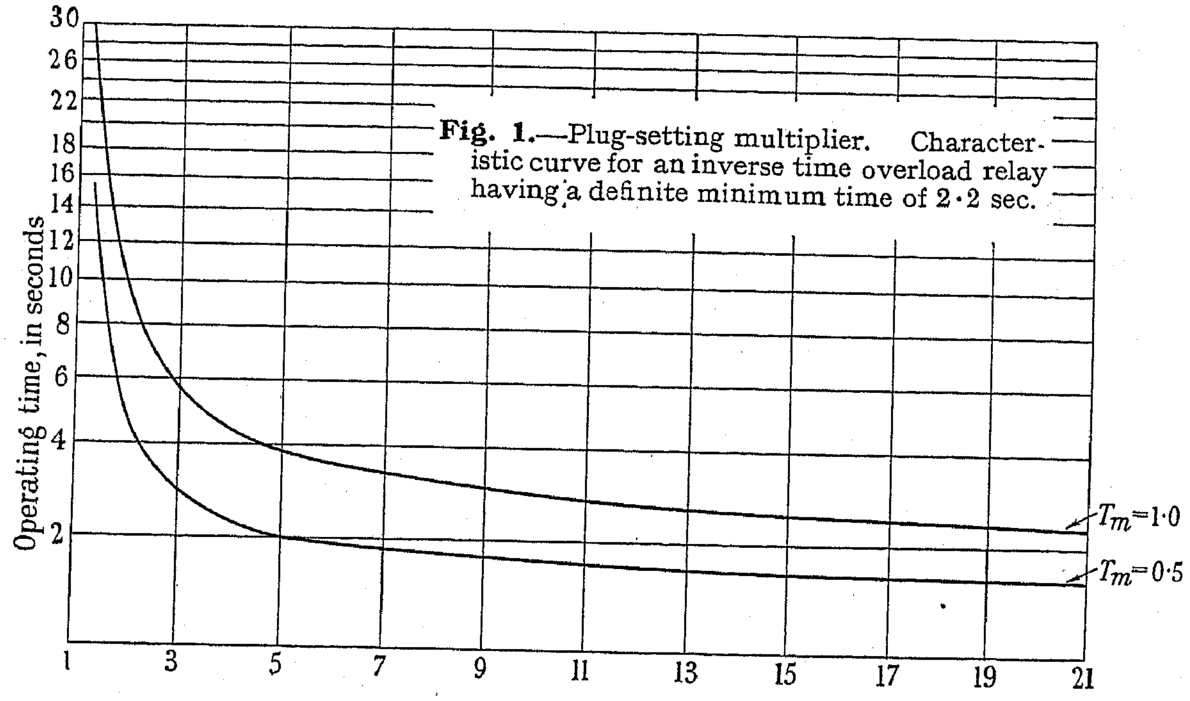


Fig. 1.—Plug-setting multiplier. Characteristic curve for an inverse time overload relay having a definite minimum time of 2·2 sec.

DIFFERENCE IN OPERATING TIME OF TWO RELAYS TO GIVE DISCRIMINATION

It has been found in practice that, if the operating times of two relays, fitted to standard-type switchgear, differ by 0·5 sec., the first relay will clear its switch and the back-up relay will return to zero without closing its trip contacts. This 0·5 sec. time difference is to cover the time between the closing of the relay contacts and the clearing of the fault, plus the time of overswing of the back-up relay due to inertia; it could clearly be altered if either of these times were reduced. One well-known overload relay has recently been re-designed to reduce overswing, and it is possible that this will lead to a reduction in the figure of 0·5 sec.

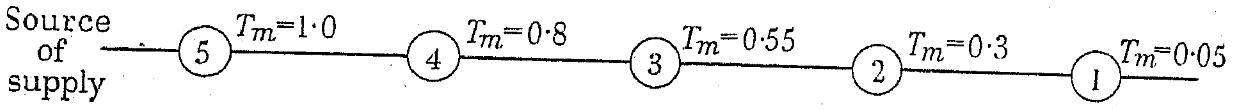


Fig. 2

GRADING ON THE ASSUMPTION THAT RELAYS ARE WORKING IN A SATURATED CONDITION

Overload relays are often graded on the assumption that the fault current will exceed the saturation value of the relay and, consequently, that the relay will be operating in its minimum time. The operating times are then only controlled by the time-setting multiplier (T_m), the plug setting being used to control the pick-up current of the relay, i.e. to protect the plant against prolonged overload. Consider the relays in Fig. 2, and suppose that they have a minimum time of operation of 2·2 sec. with a time multiplier (T_m) of 1·0. If relay 1 is given its minimum time multiplier (0·05) it will have a time of operation of 0·11 sec. Relay 2 must then have an operating time of (0·11 + 0·5) = 0·61 sec. The time multiplier of 0·3 would be used, giving a time of operation of 0·66 sec. Similarly relay 3 will have a time multiplier (T_m) = 0·55, giving an operating time of 1·21 sec. Relay 4 will have a time multiplier of 0·8, giving a time of operation of 1·76 sec. Relay 5 could be set on a time multiplier of 1·0 but it would only have a discriminating time of 0·44 sec., which might be unsatisfactory. If a slight reduction in all the time settings were made, correct operation might be obtained, but the last relay would still be operating on a time multiplier of 1·0, which might be very undesirable if the fault kVA were large.

The foregoing method gives unnecessarily long times of operation near to the source of supply. The advantages, in this respect, of the method to be described will be clear from the numerical examples given later in the paper.

FACTORS WHICH CONTROL DISCRIMINATION

It will now be shown that, unless certain precautions are taken in selecting current plug settings, incorrect operation may occur at low values of fault current.

Consider two relays in series as shown in Fig. 3(*a*).

Suppose the maximum possible fault current which can flow is known, and that current plug settings have been selected for each relay. The factors determining the selection of plug settings will be considered later.

Fig. 3(*b*) shows time/current curves for relays with a time setting of 1.

Curve A shows a time/current curve for relay 1, when relay 1 has a P.S.M. of 0·7 that of relay 2.

Fig. 3(*a*)

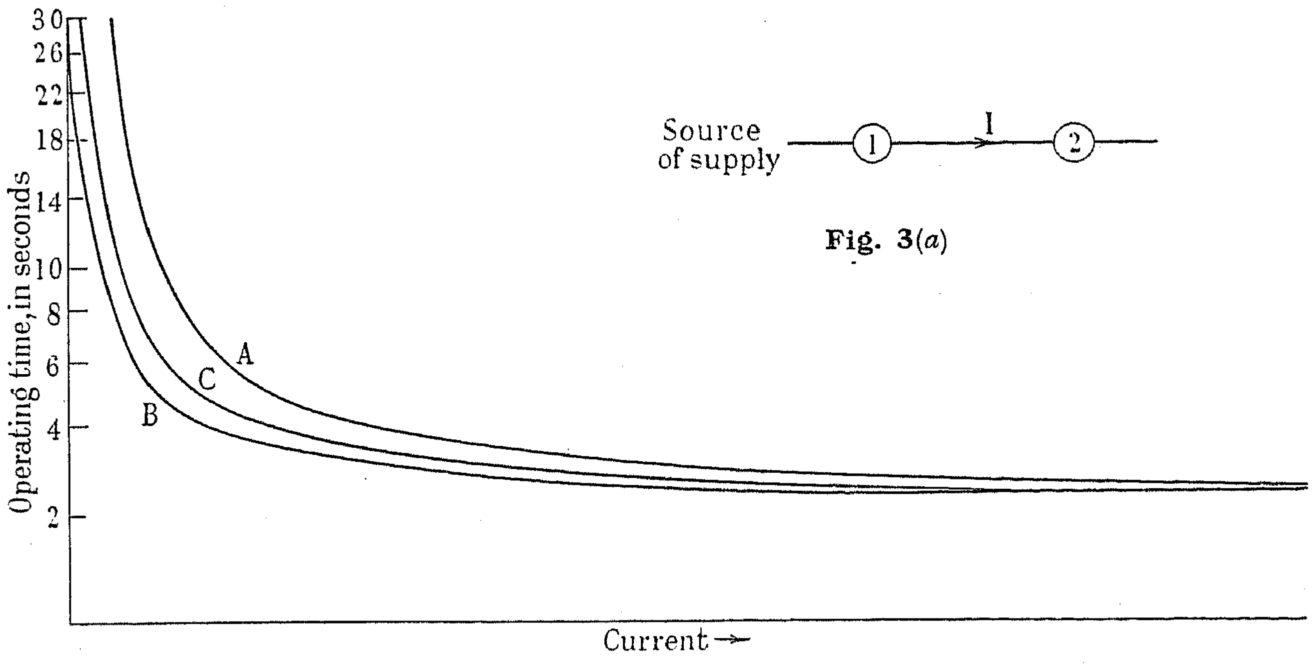


Fig. 3(*b*)

Curve A.—Time/current curve for relay 1, when relay 1 has a P.S.M. of 0·7 that of relay 2.
Curve B.—Time/current curve for relay 1, when relay 1 has a P.S.M. of 1·3 that of relay 2.
Curve C.—Time/current curve for relay 2.

Curve B shows a time/current curve for relay 1, when relay 1 has a P.S.M. of 1·3 that of relay 2.

Curve C shows a time/current curve for relay 2.

From Fig. 1, if the P.S.M. is the same in each case, for different time-setting multipliers, the discriminating time will increase as each operating time increases. From Fig. 3(*b*) it is clear that, if the P.S.M. of relay 1 is greater than that of relay 2, the operating time of relay 2 (Curve C) will increase faster than that of relay 1 (Curve B) as we approach pick-up current on the curve. Thus there is a danger that the discriminating time will be seriously decreased on small values of fault current. If, however, the P.S.M. of relay 1 is less than that of relay 2 it can be seen from Curves A and C that the discriminating time will increase. Therefore, provided the P.S.M. of relay 1 is equal to, or less than, that of relay 2, discriminating time will always be equal to, or greater than, that for the maximum fault current.

SELECTION OF PLUG SETTING

To illustrate the method, the case of three relays in series is considered in Fig. 4. Relay 3 is given the lowest possible plug setting (P_m), consistent with stability under load and discrimination with transformer protection. Relay 2 is given a plug setting such that the P.S.M. for relay 2 is equal to, or less than, that of relay 3. The plug setting of relay 2 should also be such that the relay is operating in its minimum time (i.e. under saturated conditions) for a fault at its own end of the feeder between 3 and 2. It will usually be found that the two conditions given above can be satisfied by a range of plug settings; if so, the largest should be chosen, consistent with its fulfilling its function as a back-up to relay 3. The higher the plug setting chosen, the lower the time setting required to give the necessary time of operation to relay 2, when backing-up relay 3. The result of the lower time-setting multiplier will be faster operation as relay 2 approaches saturation. The lower time-setting multiplier of relay 2 will also be reflected in that of relay 1. The above process is repeated to select a plug setting for relay 1.

SELECTION OF TIME-SETTING MULTIPLIER

It remains to determine the time settings for the relays in Fig. 4. The time setting of relay 3 is made as low as possible, consistent with it discriminating with any gear beyond it. The time setting of relay 2 is then chosen to give 0·5 sec. time difference between relay 2 and relay 3 for the maximum fault current in relay 2 and relay 3. The time setting for relay 1 is obtained in a similar way for the maximum fault current through relay 1 and relay 2. It is helpful to record the operating times and plug-setting multipliers on diagrams to form a permanent and compact record of the calculation. The diagrams also show at once if the P.S.M. decreases towards the source of supply. The points raised in regard to plug setting and time setting will be made clear by the numerical example which follows.

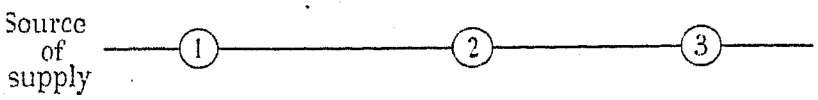


Fig. 4

NUMERICAL EXAMPLE

Fig. 5(*a*) shows a simple system in which substations are fed in series on one feeder from a station A having a fault MVA of 300. The value of this quantity is shown at each substation.

Fig. 5(*b*) shows the current for a 3-phase tail-box fault on the outgoing feeder at E, namely 2 620 amp. Whichever method of grading is used, the end relay at E must clearly be set at the lowest possible setting, consistent with stability and discrimination with other protected apparatus beyond it. Generally the presence of a transformer assists this. Relay E will therefore have a time-setting multiplier of 0·05 and a plug setting depending upon the load, size of feeders, etc., say in this case 100 %, giving a full-load current of 50 amp. and a pick-up current of $1\cdot3 \times 50 = 65$ amp. The P.S.M. for relay E is $2\,620/50 = 52\cdot4$ times full load, which is well over saturation value. The time of operation is $2\cdot2 \times 0\cdot05 = 0\cdot11$ sec. Therefore, to ensure discrimination, the relay at D must operate in $0\cdot11 + 0\cdot5 = 0\cdot61$ sec.

On the saturation method, the plug setting of relay D would probably be 100 %, giving a P.S.M. of $2\,620/100 = 26\cdot2$ times full load, which is again well over saturation value. The time-setting multiplier must then be $0\cdot61/2\cdot2 = 0\cdot3$ approx. Now, by altering the plug setting to 200 %, the full load is 200 amp. and the P.S.M. $= 2\,620/200 = 13\cdot1$ times full load. Reference to Fig. 1 gives a time of operation of 2·6 sec. with a time-setting multiplier of 1·0; with a time-setting multiplier of 0·25 a time of operation of $2\cdot6 \times 0\cdot25 = 0\cdot65$ sec. is obtained.

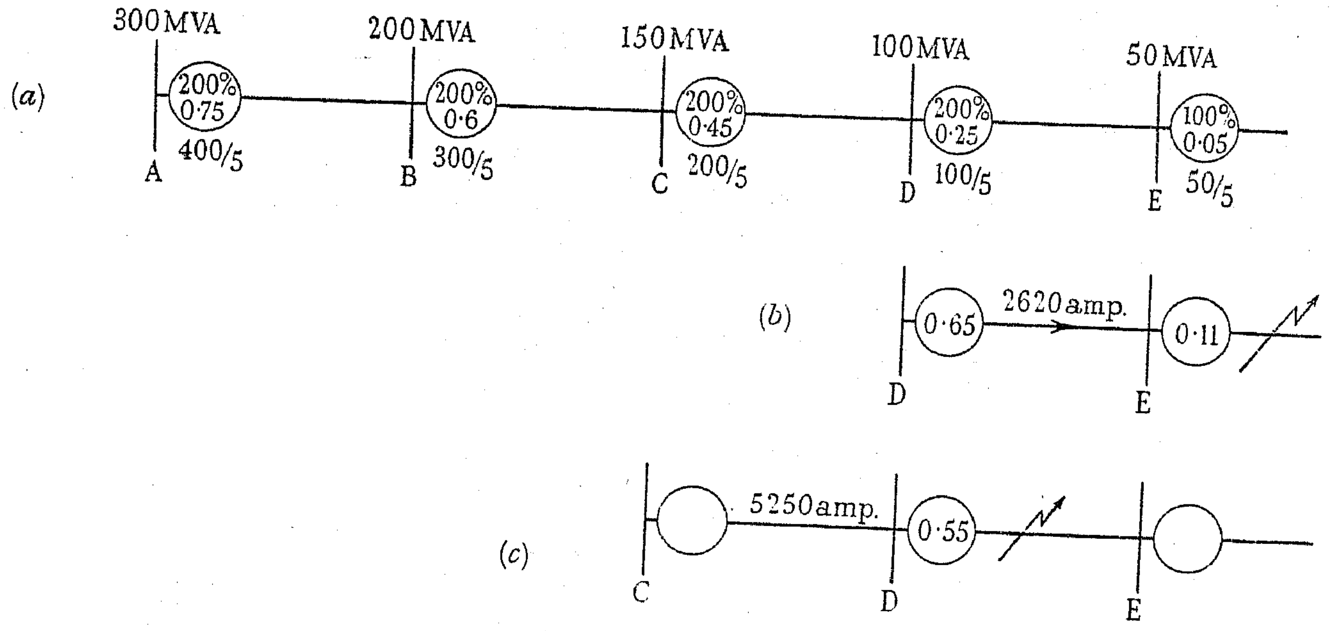


Fig. 5

Sub-station	Plug-setting method		Saturation method	
	Setting	Min. time	Setting	Min. time
A	200 %, 0·75	sec. 1·65	100 %, 1·0	sec. 2·2
B	200 %, 0·6	1·32	100 %, 0·8	1·76
C	200 %, 0·45	0·99	100 %, 0·55	1·21
D	200 %, 0·25	0·55	100 %, 0·3	0·66
E	100 %, 0·05	0·11	100 %, 0·05	0·11

For a fault on the outgoing feeder from D, as shown in Fig. 5(*c*), the short-circuit current is 5 250 amp., giving a P.S.M. of $5\,250/200 = 26\cdot25$, which is greater than the saturation value. Relay D will therefore operate in $2\cdot2 \times 0\cdot25 = 0\cdot55$ sec., thus reducing the time of operation by $0\cdot66–0\cdot55 = 0\cdot11$ sec. as compared with the saturation method. Continuing this system throughout gives the settings shown in Fig. 5(*a*). Table 1 shows a comparison between the times of operation given by the two methods for a 3-phase fault on the outgoing feeder from the substation concerned. It will be seen that by grading the plug settings a reduction of 0·55 sec. has been obtained at substation A.

THE PLUG-SETTING METHOD IN PRACTICE

A portion of the network to which the plug-setting method has been applied in practice is shown in Fig. 6; fault MVA, current-transformer ratios, and relay settings, are shown. The process of grading is shown in Figs. 7(*a*) to 7(*n*). The first step is to set relays A and B; these can be set on their minimum settings of 50 % and 0·05, for with a healthy system power is always flowing into Substation 3. C and D must then be set to discriminate with A and B. Fig. 7(*a*) shows the fault which gives the maximum current through A and C, i.e. the switch open at D. The method previously described is then applied to obtain the setting of C; D will clearly have the same setting as C. Fig. 7(*b*) is a check to show that relay A is still operative for the smallest 3-phase fault between A and D. The grading of relay H is shown in Fig. 7(*c*); 473 amp. is the maximum current through C and H, it being less when the ring main is closed, as shown in Fig. 7(*e*). Relay G is similarly graded in Fig. 7(*d*). Relays F and I can clearly have a minimum time setting of 0·05, and the 200 % setting on a 50/5 current transformer gives stability under load conditions if the ring main is open. A setting for E is found in Fig. 7(*f*), and the setting checked against the existing setting of G in Fig. 7(*g*). J is graded against H in Fig. 7(*h*).

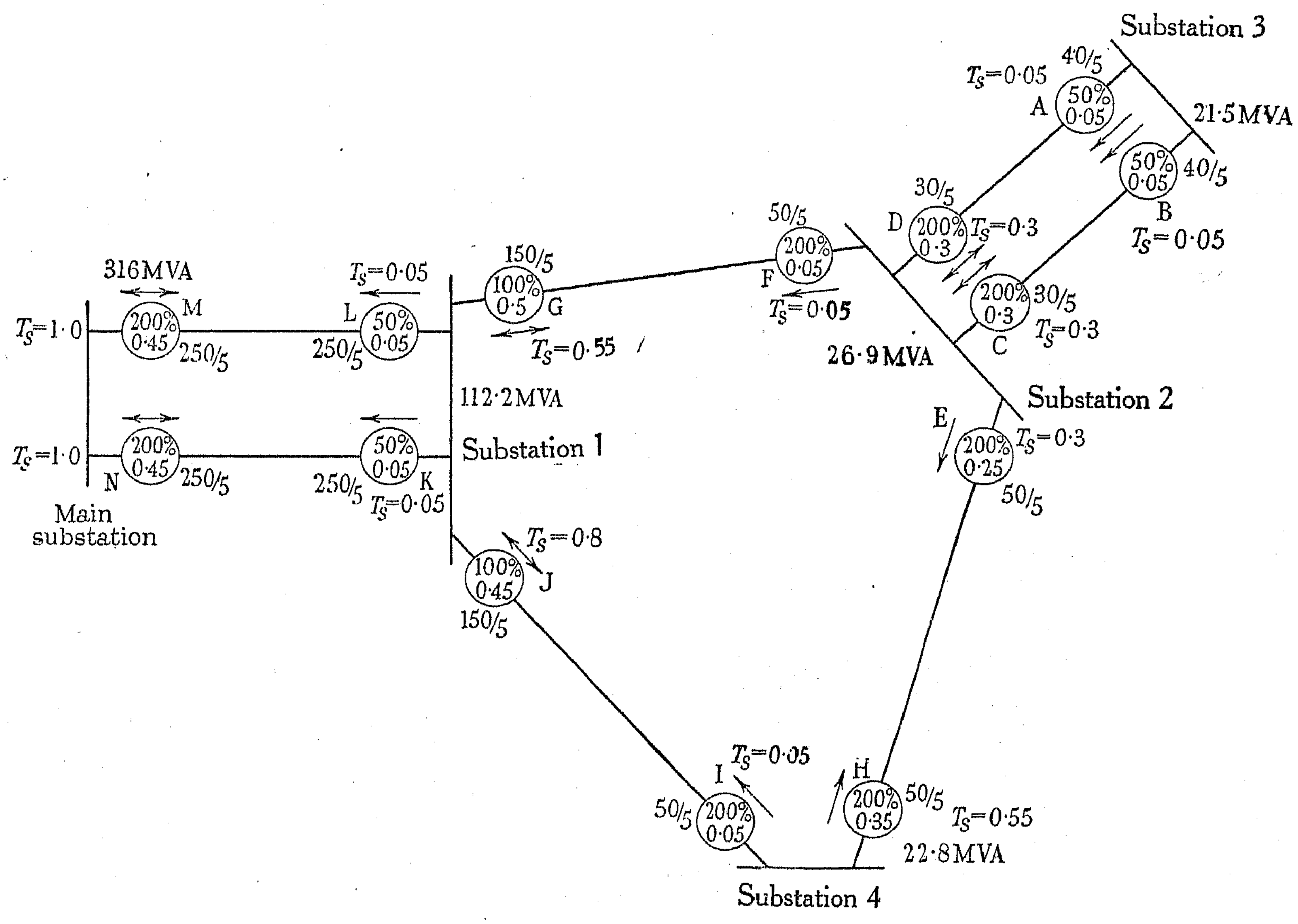


Fig. 6

Figs. 7(*i*) to 7(*l*) check the settings for back-up conditions in the event of a relay failing. L and K can clearly be set on their minimum settings. Fig. 7(*m*) shows the grading of relays M and N and it will be seen that two feeders in parallel have been considered in this diagram and not the case giving the maximum current down any feeder, that is when only one feeder is in commission; this has been done because the main substation is attended and, in the event of a feeder tripping out, the control engineer can reset the relay to a time multiplier of 0·55 in place of the normal setting of 0·45. The plug-setting multipliers have been shown on each of the fault diagrams and it will be seen that their value decreases towards the main substation.

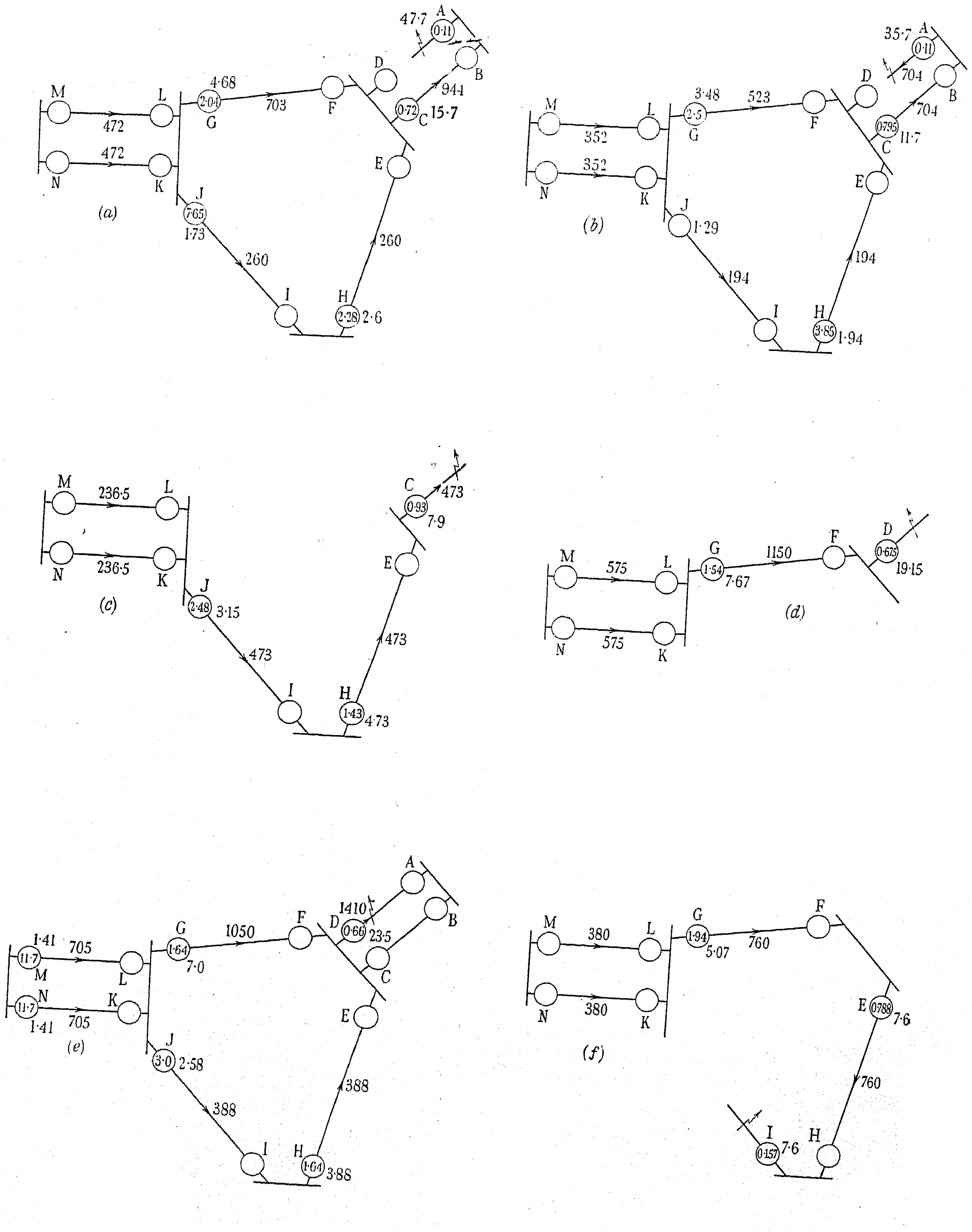
Reference must be made here to Fig. 7(*n*), which checks the parallel-feeder condition considered later in the paper. It will be seen that relay G does not quite fulfil the necessary back-up condition, but this is allowable as relay H does and therefore maintains supply. This will be made clear if reference is made to the section on parallel feeders.

Fig. 8 shows another circuit operating in practice with the time-setting multiplier obtained by both methods. The saturation-method settings are labelled T.S.

PARALLEL FEEDERS

The case of substations fed by parallel feeders, as shown in Fig. 9, is interesting. Consider a fault at F almost on the busbars of substation B. The impedance from B to the fault will be small compared with that round the loop BCF, and therefore, until switch 6 has cleared, very little current will pass through switches 5 and 8 and the relays on those switches will be inoperative. The time of operation of any one of these relays is, therefore, its operating time for a fault at F with switch 6 open, plus the operating time of switch 6. If relay 8 fails to operate, relay 5 should operate as a back-up. It is therefore necessary to find the operating time of relays 1 and 2, to ensure that it is longer than that of relay 5, if this back-up condition is to be checked. The following method is suggested:—

Calculate the operating time of relays 1 and 2 for the case when the switch 6 is closed; call this time T_1. Suppose the operating time of 6 is T_2. Then, when the relay 6 has operated, relays 1 and 2 have covered T_2/T_1 of their travel, and have $[1 - (T_2/T_1)]$ of the travel to go. The time of operation of 1 and 2 is now calculated for the fault at F with switch 6 open. Suppose this is T_3. The remaining time of operation of relays 1 and 2 is therefore $[1 - (T_2/T_1)] \times T_3$. The total time of operation is $\left\{[1 - (T_2/T)_1] \times T_3\right\} + T_2$. It is suggested that this time should exceed the total operating time of relay 5 by 0·8 sec. and not 0·5 sec. as relays 1 and 2 have, in effect, two overruns—when the current changes, and when the relay reaches the end of its travel. The above method probably gives a longer operating time than is actually obtained in practice, but forms a basis for checking.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472
N
K
E
J
7·65
1·73
260
260
I
H
2·28
2·6
(a)
35·7
A
0·11
704
D
B
704
3·48
523
M
L
2·5
G
F
0·795
C
11·7
352
352
N
K
E
J
1·29
(b)
194
194
I
H
3·85
1·94
C
0·93
473
7·9
M
236·5
L
N
236·5
K
E
J
2·48
3·15
(c)
473
473
I
H
1·43
4·73
D
0·675
19·15
G
1150
F
M
575
L
1·54
7·67
(d)
N
575
K
A
1410
B
D
0·66
23·5
G
1050
F
C
1·41
705
11·7
M
L
1·64
7·0
11·7
N
K
1·41
705
E
(e)
J
3·0
2·58
388
388
I
H
1·64
3·88
G
F
M
380
L
1·94
5·07
760
N
380
K
E
0·788
7·6
(f)
760
I
0·157
7·6
H

Fig. 7

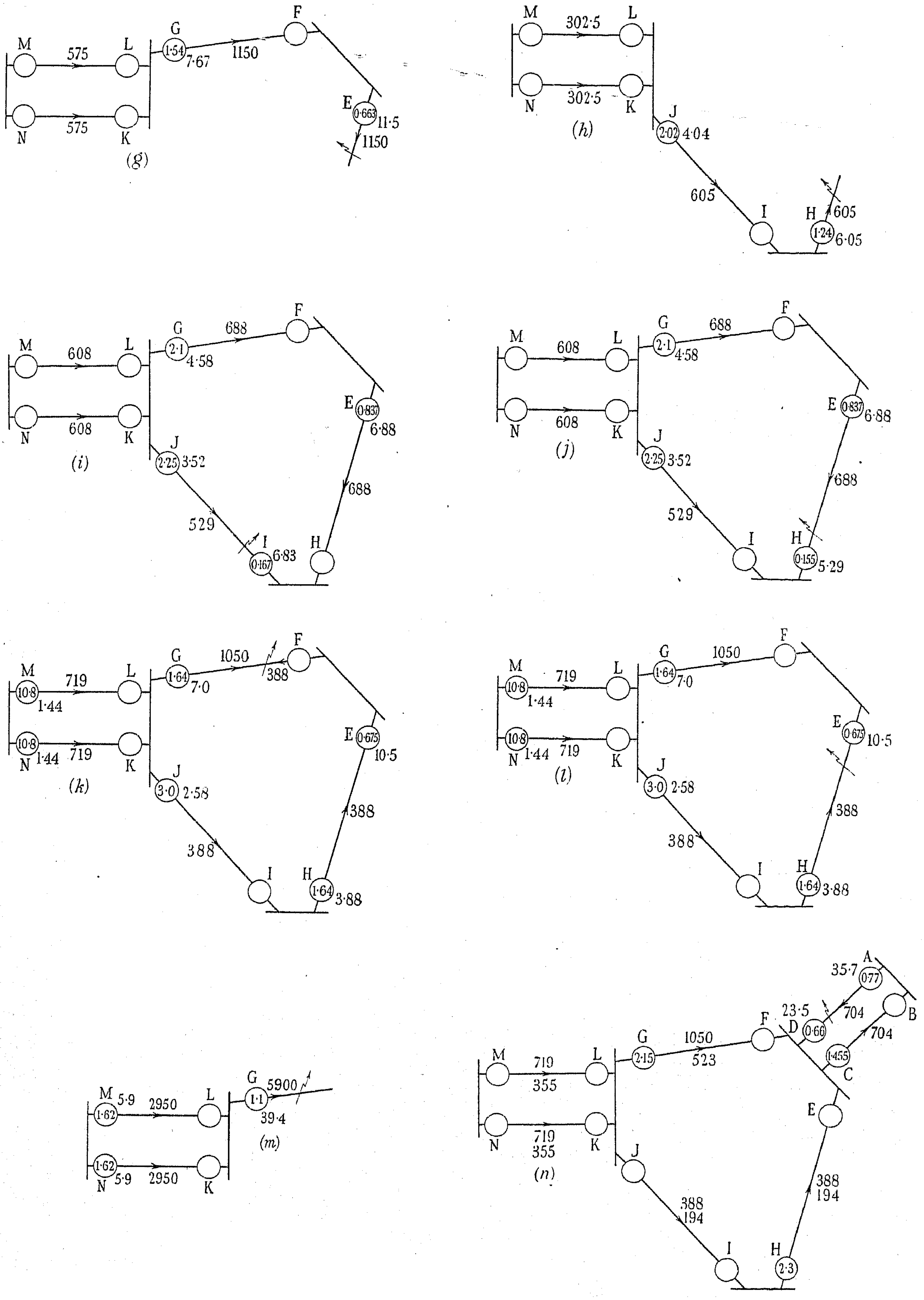
M
575
L
G
1·54
7·67
1150
F
N
575
K
E
0·663
11·5
1150
(g)
M
302·5
L
N
302·5
K
(h)
J
2·02
4·04
605
I
H
1·24
605
6·05
M
608
L
G
2·1
688
4·58
F
N
608
K
E
0·837
6·88
(i)
J
2·25
3·52
688
529
I
0·167
6·83
H
M
608
L
G
2·1
688
4·58
F
N
608
K
E
0·837
6·88
(j)
J
2·25
3·52
688
529
I
H
0·155
5·29
M
10·8
719
1·44
L
G
1·64
1050
7·0
388
F
10·8
N
1·44
719
K
E
0·675
10·5
(k)
J
3·0
2·58
388
388
I
H
1·64
3·88
M
10·8
719
1·44
L
G
1·64
1050
7·0
F
10·8
N
1·44
719
K
E
0·675
10·5
(l)
J
3·0
2·58
388
388
I
H
1·64
3·88
A
35·7
0·77
B
23·5
704
D
0·66
704
F
1·455
C
G
2·15
1050
523
M
719
355
L
E
N
719
355
K
(n)
J
388
194
388
194
I
H
2·3
M
1·62
5·9
2950
L
G
1·1
5900
39·4
(m)
1·62
N
5·9
2950
K

Fig. 7 (*contd.*)

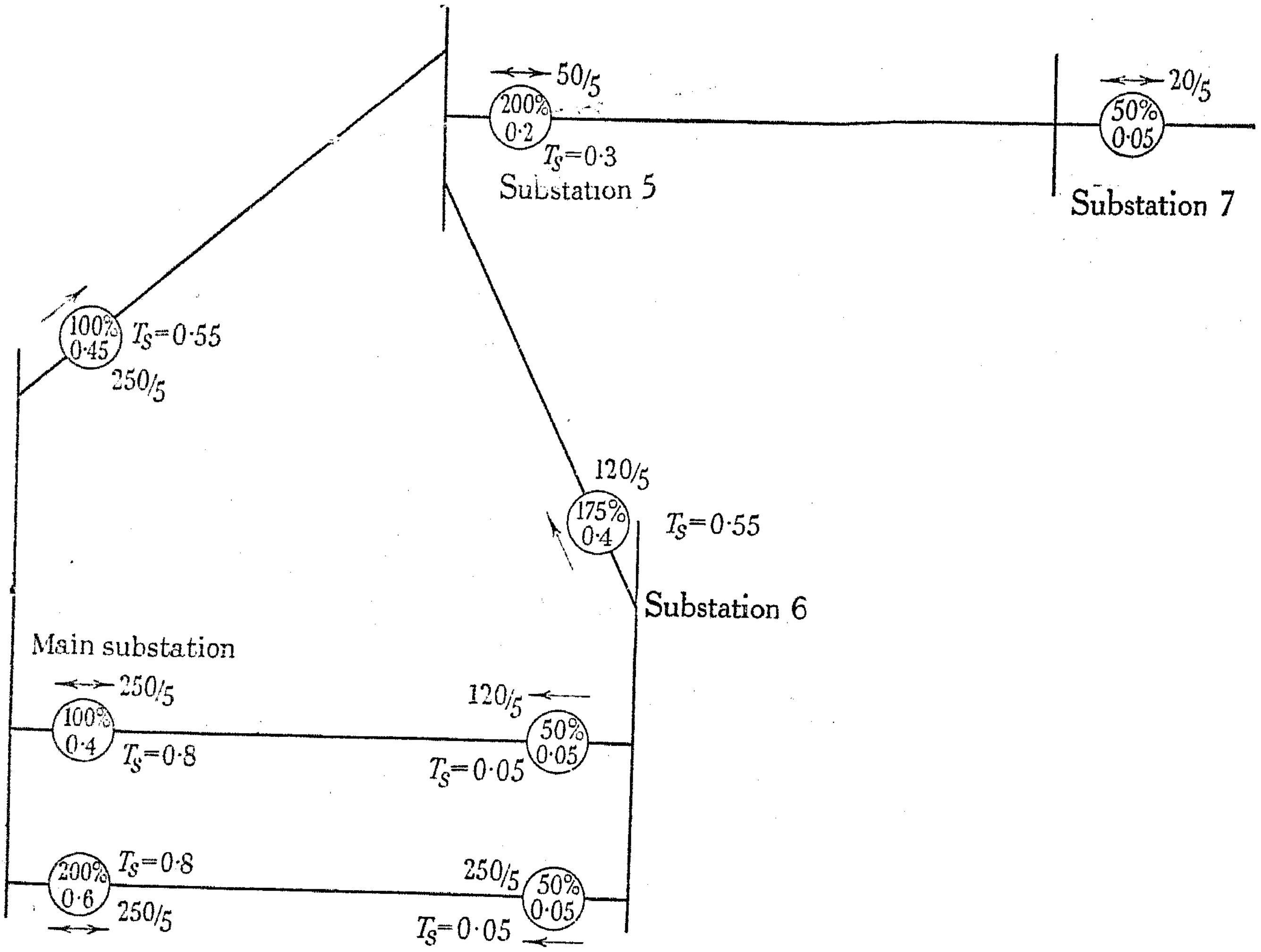

Fig. 8

DAMAGE TO CABLES

In a recent paper* before The Institution, the late Mr. Clothier and Messrs. Leeson and Leyburn gave a graph showing the maximum time for which certain sizes of cable can safely withstand various short-circuit currents. Curve A of Fig. 10, for a 0·25-sq. in., 11-kV, 3-core cable, is obtained from this graph. Curves B and C show the times for clearing a fault on the breakers at M and N in Fig. 6, assuming 0·2 sec. to be the total break time. The points where B and C cut A give the maximum fault current that the relay can clear without damaging the cable. These points are 10·25 and 14·7 kA respectively. Fig. 11 shows the value of the fault current for various distances from the main substation and it is clear that the saturation setting leaves approximately 2 500 yards unprotected, whereas the plug-setting method leaves only 580 yards unprotected.

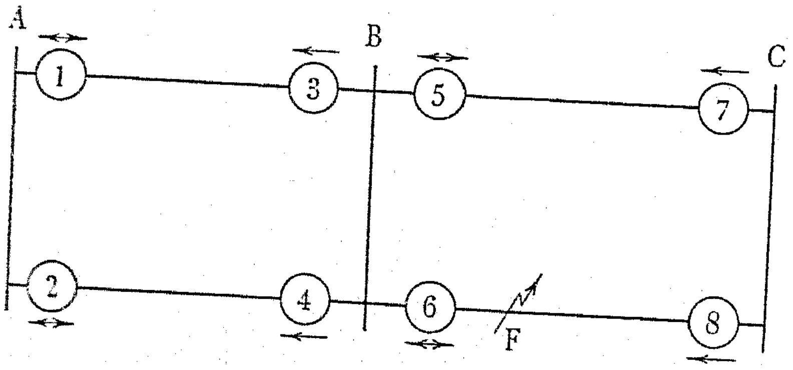

Fig. 9

It is necessary to clear the maximum fault current of 16 600 amp. in 0·9 sec. in order completely to protect the cable. In the case of smaller cables, or where a large number of relays are used in series, it is often impossible to protect a cable completely by employing overload relays, and other methods of faster-acting protection must

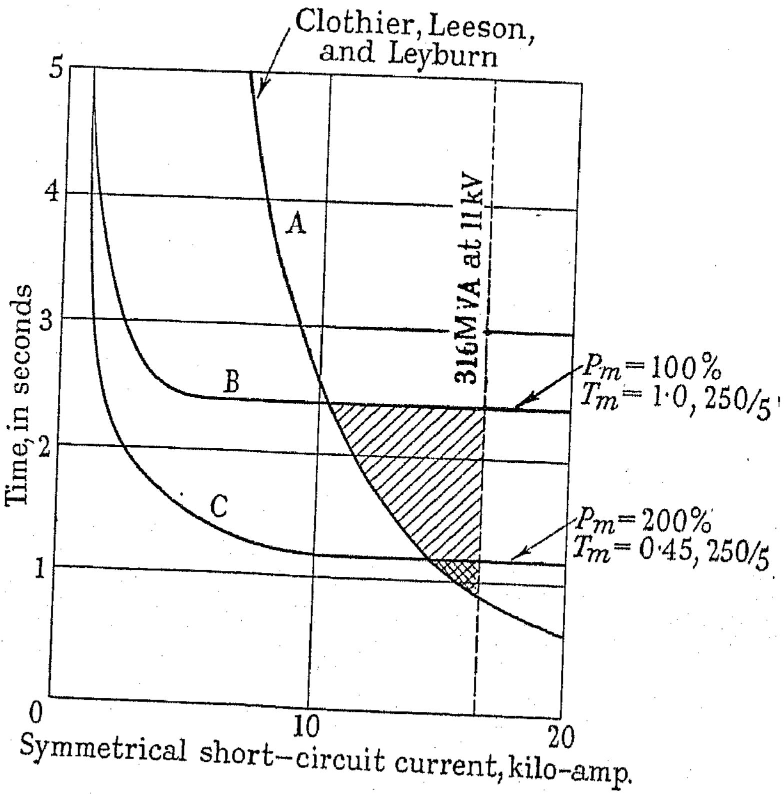

Fig. 10

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* *Journal I.E.E.*, 1938, 82, p. 445.

be used. The authors feel that this criterion of the limitation of overload protection cannot be too strongly emphasized.

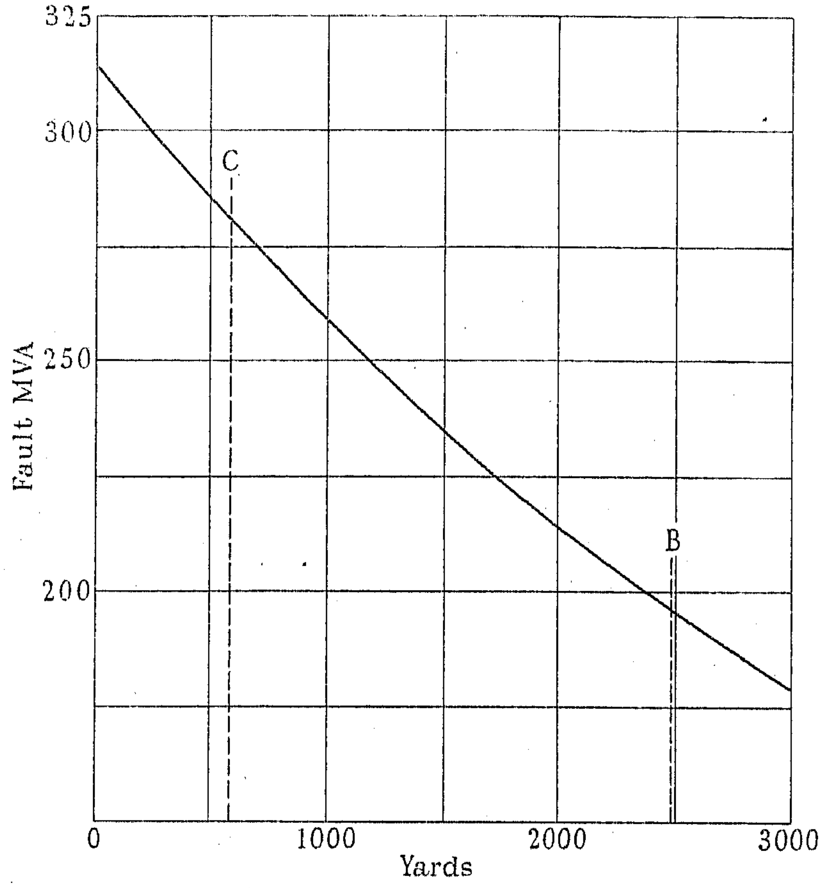

Fig. 11.—Calculation based on one 0·25-sq. in. cable at 11 kV.

ROUTINE METHODS OF CALCULATION

The system described requires a very complete record of all calculations. The authors have developed a method of calculation whereby a number of diagrams form the permanent record. Firstly, a line master diagram is made showing the lengths, sizes, percentage resistances and percentage reactances, of all feeders and current-transformer ratios, total impedance, and fault kVA, at each substation. Large circles are drawn to represent the relays, and various markings indicate their types. A section of this diagram is shown in Fig. **12.** A permanent record of the system constants is thus provided. The circuit to be protected is extracted from the master diagram and a number of line diagrams prepared, on each of which is marked the position of a fault and the magnitude and distribution of the fault current, as in Fig. 7. The relay settings are recorded on another line diagram as in Fig. **6.** The time of operation is marked in every relay circle on each fault sheet, and as each fault is considered the necessary alterations are made to the setting diagram and the times of operation on the previous fault sheets. All fault sheets should show the minimum discriminating time of 0·5 sec. and consecutive decreasing or equal P.S.M.'s towards the supply. When these diagrams have been completed a further set of diagrams must be prepared, with various circuit-breakers open, and the settings checked to see that discrimination is obtained. Sometimes small modifications cover these conditions; in other cases, however, the condition must be relegated to a set of emergency settings. Whether such a set of emergency conditions is justified

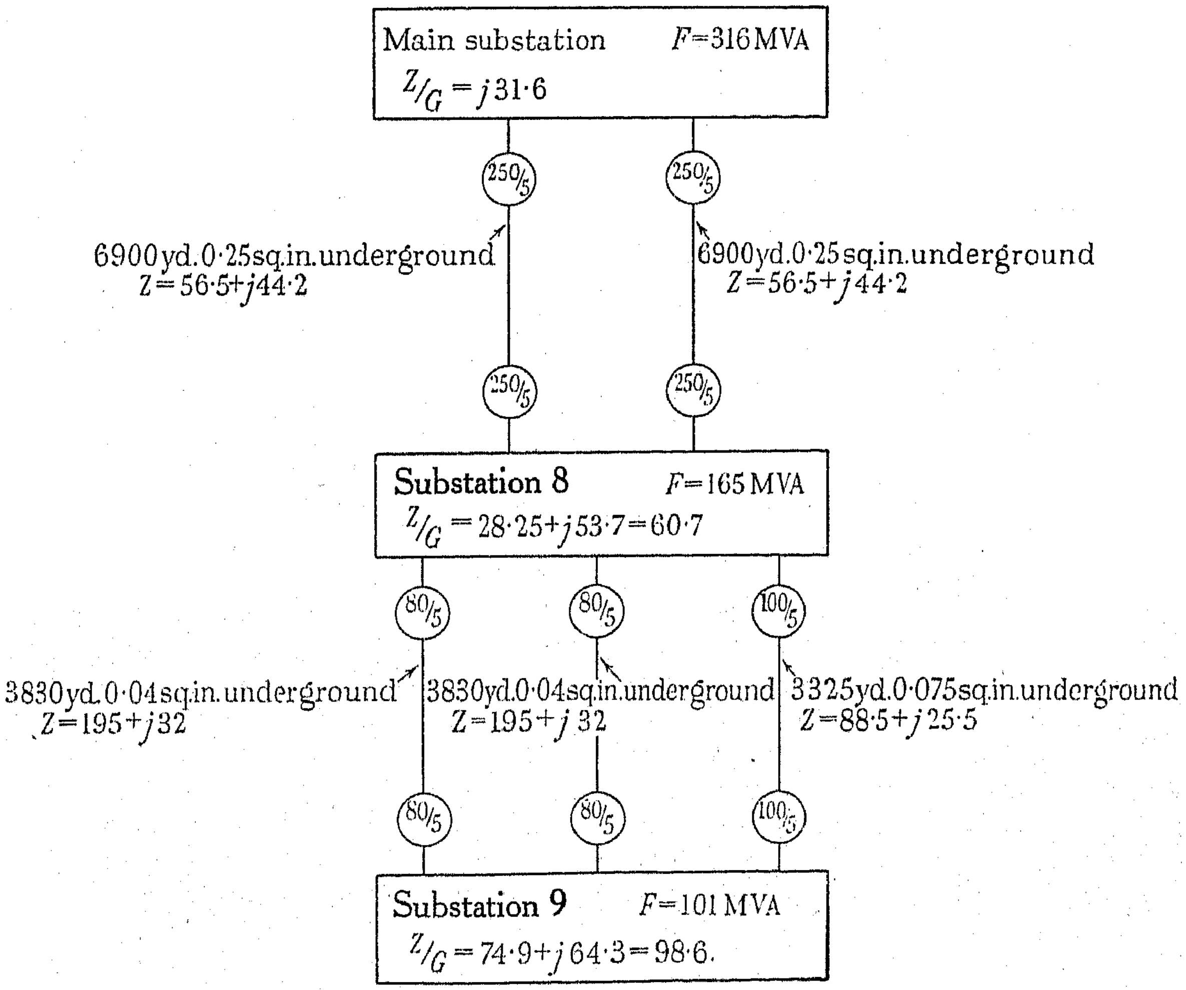

Fig. 12

Z/G = percentage impedance to substation, based on 100 MVA.
F = fault MVA.

depends upon the probability of the circuit conditions being changed for a long period, and the seriousness of incorrect sequence operation. It is as well to have these conditions worked out and a set of diagrams prepared showing each emergency condition and the settings required. The control engineer is then in a position to judge for himself from the diagrams whether alterations are necessary, and is able to estimate the effect of a second fault. Where overload is only used as a form of back-up protection, emergency settings will probably be completely unjustified. It is a good plan to provide each relay with a card on which are shown the normal settings; this provides an automatic check when the relay is put back on its normal setting, after emergency conditions or after a tripping test.

CONCLUSIONS

The plug-setting method has been found to present several marked advantages in practice, chief among which is the considerable reduction in tripping times obtained. Thus reduction in the effects of system surges due to short-circuits has been most marked. While the method requires considerable initial labour in its preparation, the maximum amount of plant within the range of the relay is protected.

ACKNOWLEDGMENT

The authors wish to thank the Bournemouth and Poole Electricity Supply Co., Ltd., for permission to publish network data.

WRITTEN CONTRIBUTIONS TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. C. Freeland: The possibilities of the plug-setting method, and its advantages over what the authors refer to as the saturation method (i.e. grading on the time setting alone), are too rarely appreciated. Where extensive networks are to be considered, the application of this method is essential if an adequate degree of discrimination is to be obtained.

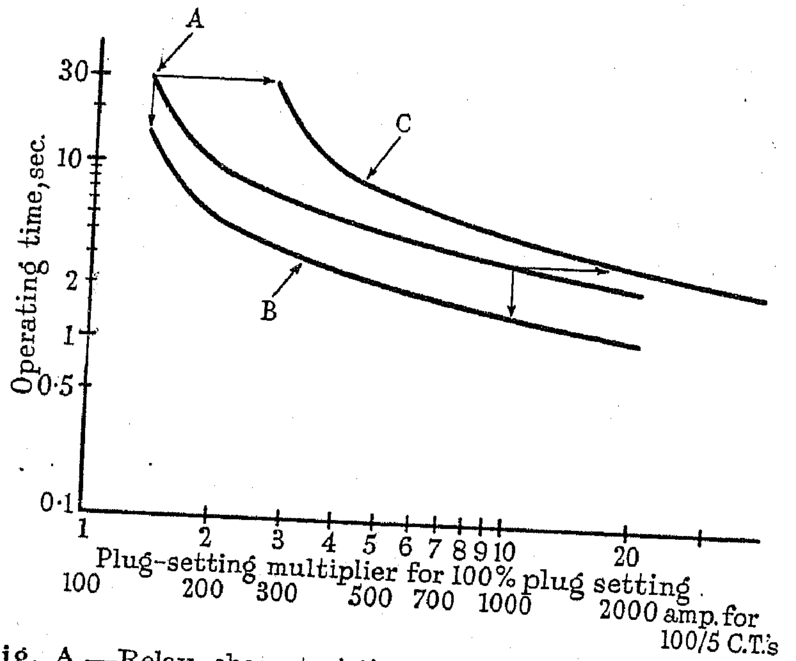

Fig. A.—Relay characteristics to logarithmic current and time scales.

Curve A.—100 % plug setting, 1·0 time-setting multiplier.
Curve B.—100 % plug setting, 0·5 time-setting multiplier.
Curve C.—200 % plug setting, 1·0 time-setting multiplier.

On such systems, however, involving a large number of relays, the calculations involved by the plug-setting method tend to become very unwieldy if analytical methods such as are indicated in the paper are adhered to. In this connection it should be remembered that it is unusual to arrive at a final setting for a relay at the first attempt, and that the setting finally decided upon is usually a compromise between several conflicting points, namely stability on load, adequate discrimination and a sufficiently short time-lag at the main stations. Much of this routine work can be saved by the use of the following simplified method, which can be compared to slide-rule as opposed to arithmetical procedure.

Fig. A shows the relay characteristics given in Fig. 1 of the paper, plotted to logarithmic scales on both time and current axes, together with an additional scale of current assuming that 100/5 current transformers are used, the plug setting being 100 % in the case of the curves transcribed from the paper. The additional curve C is for a relay set at 200 % plug-setting and 1·0 time-setting multiplier. It will be seen on examination that these curves are identical in shape, but that the 0·5-sec. curve has been moved bodily downward by a distance equal to the length from 1 sec. to 0·5 sec. on the time scale, i.e. the procedure for multiplying by 0·5 using a slide-rule. Similarly, to obtain the 200 % plug setting, the curve is moved to the right. This operation becomes very simple if a transparent template, as shown in Fig. B, is used to draw the curves.

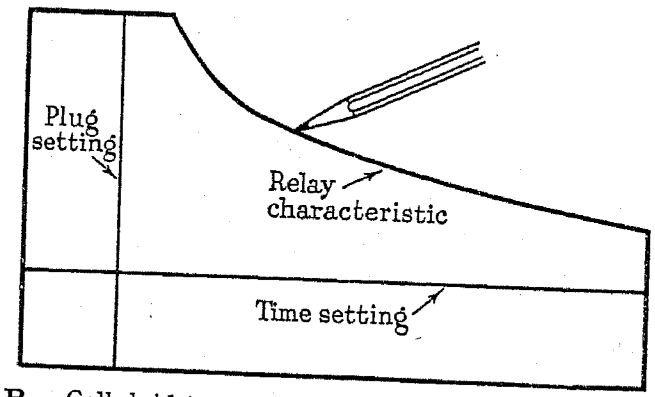

Fig. B.—Celluloid template for plotting relay characteristics.

Considering the example given on pages 115 and 116, the procedure is as follows: A setting is selected for Relay E as described by the authors, and its curve is plotted by means of the template as indicated in Fig. C. In order to obtain the necessary 0·5-sec. discrimination the curve for Relay D must not approach that of E by less than 0·5 sec. at any value of current up to the maximum that can flow. A suitable setting can thus be quickly settled for Relay D, and hence for the remainder of the system. After the final settings have been decided the finished curves can be used as a permanent record of the system, as shown in Fig. C.

In the case of more complicated networks the procedure is identical, except, of course, that the additional complications naturally entail more adjustment of the settings before a final decision can be reached; but it has been found in practice that, with use, the manipulation of the template becomes instinctive, just as the use of the slide-rule becomes instinctive, and that the length of time involved in settings calculations is cut down to a very small percentage of that normally involved by arithmetical methods. Where relays of different types are in use on a network, a further advantage is gained in that the effect of the different characteristics on discrimination is indicated at once.

Mr. H. J. Fraser: The authors' methods of calculating relay settings are interesting, but there must be few networks where this type of relay can be successfully employed except for "back-up" protection purposes. The principal difficulty appears to be that the relay nearest to the feeding point must always have a time-multiplier setting approaching unity, and as this is also the point at which the fault kVA reaches a maximum it is most undesirable that a clearing time approaching 2 sec. be permitted.

Where fault currents of any magnitude are experienced, the voltage-dip on quite large networks is often extensive, and if the fault is not cleared very quickly interference with d.c. supplies through rotary plant or mercury-arc rectifiers is not an uncommon experience.

If the inverse-time overload type of relay is to be relied upon to clear faults then it would appear that it could with advantage be redesigned to give a definite minimum time much less than the present 2·2 sec., without seriously interfering with the normal overload timings.

Overswing of overload relays due to inertia is a serious drawback, and it is interesting to note the authors' remark that one manufacturer has redesigned an overload relay to give better damping, as this means more reliable operation under switching-surge conditions where the time-multiplier setting approaches 0·05.

Have the authors had any experience of the grading of combined overload and earth-leakage relays? For overhead systems in particular it is usual to have two overload elements with the standard plug settings 50 % to 200 %, whilst the earth-leakage element is graded from 10 % to 70 %. Unfortunately the use of the lower plug settings on the earth-leakage element produces some strange results, and it has been noted that the primary earth-fault currents required for relay operation are much in excess of the theoretical values. Where the current transformer is approaching full load the fault current required for relay operation may be more on the lower than on the higher plug setting, and this obviously leads to faulty operation of the protective system. This peculiarity appears to be due to the combined characteristics of current-transformer and relay windings. On no-load the current-transformer winding has considerable impedance, but this decreases as the load increases. On the other hand the relay windings are usually designed for constant VA consumption over the range of plug settings, and the impedance on the lower plug settings may be very high.

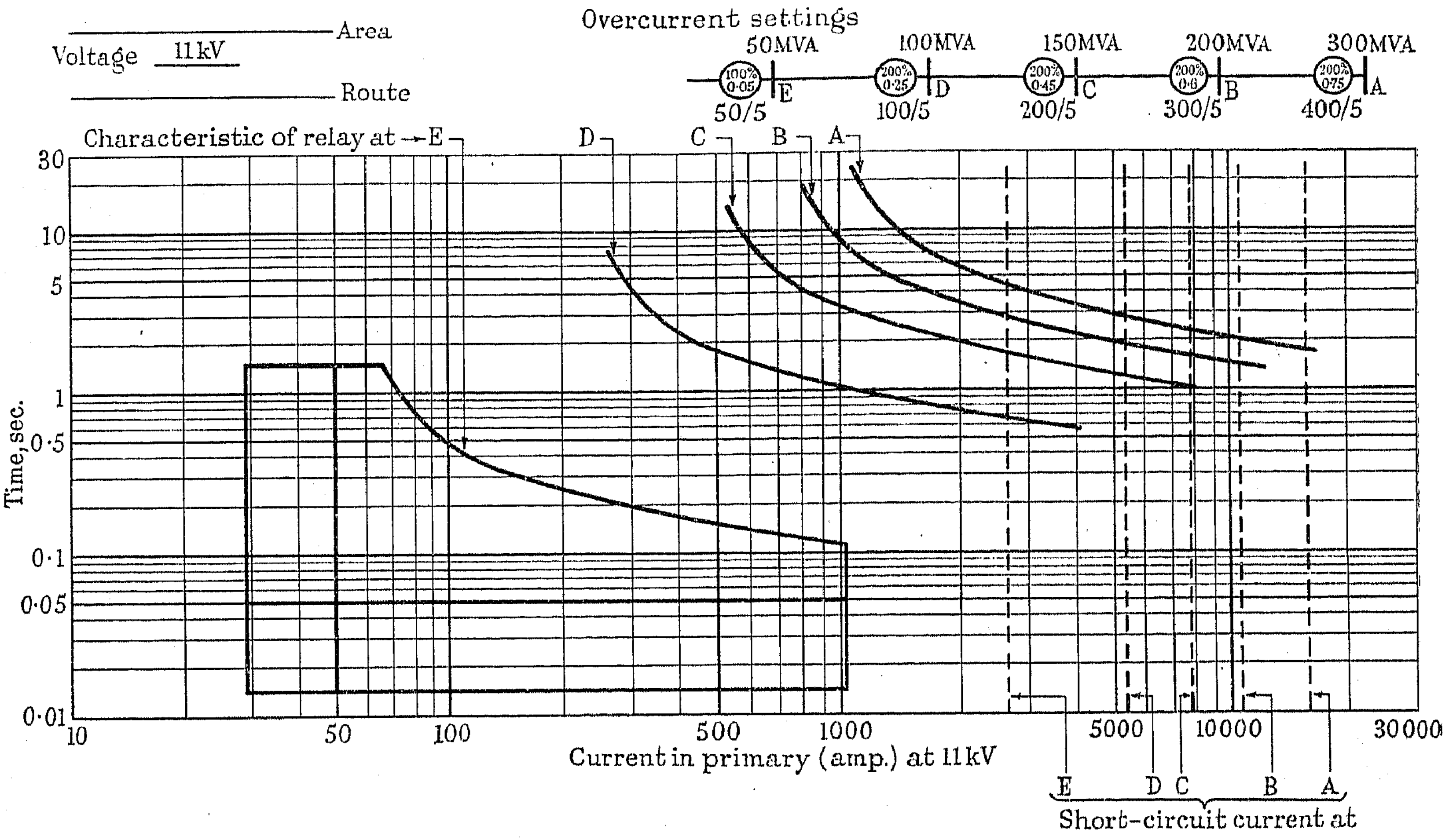

Fig. C.—Calculation chart for system as illustrated in Fig. 5, showing template in position for characteristic of relay at E, i.e. plug setting 50 amp., time-setting multiplier 0·05.

A high impedance in the fourth wire of the relay circuit appears to account for the increased values of primary earth-fault current required for operation of the earth-leakage element.

Mr. J. A. Grieveson: Although the inverse-time overcurrent relay is in such common use, it is too frequently taken for granted and its application correspondingly misunderstood.

The authors rightly emphasize the importance of accurate and detailed fault-current analysis in the development of any protective scheme, and their method of setting out the system impedances, fault kVA and other details on the master diagram is worthy of note. It is remarkable how often the relay manufacturer is asked to recommend settings for time-discriminative relays on systems of which little more seems to be known than the rated rupturing capacity of the substation switchgear.

In such cases the "saturation" method, as the authors term it, is the only possible basis of calculation. It offers, moreover, the decided advantage that, if the requisite time-intervals between successive switches can be obtained for the assumed high values of fault current, discrimination will be doubly assured for any lower values experienced in service. Unfortunately, discrimination between the various relays on the particular network under consideration is not the only criterion, and it is also necessary to take into account other factors which may limit the maximum permissible time setting. One such factor, as outlined in the paper, is the thermal rating of any cables on the system; another, and a more common one nowadays, is the time setting of overcurrent relays on incoming bulk-supply feeders. If such limitations make it imperative to reduce the time settings below the values given by the "saturation" method, then the "plug-setting" method must be used.

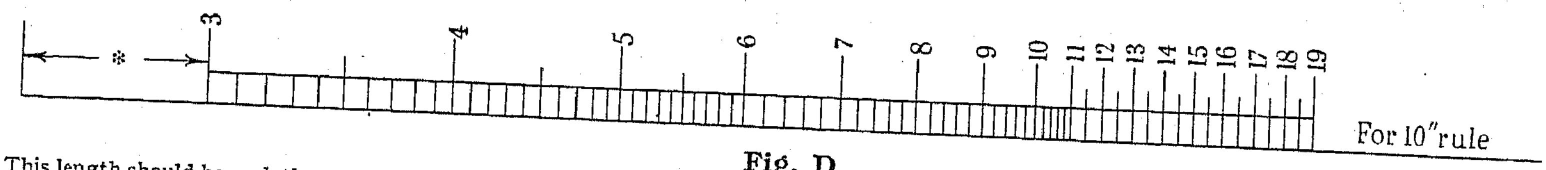

Fig. D

* This length should be such that when the R.H. end of the slide of the slide rule touches the L.H. end of this scale the following readings are obtained:—

This scale (P.S.M.) 6
Scale C 10
Scale D (time of relay) .. .. 3·8

The paper shows that for satisfactory discrimination the P.S.M. values at consecutive switches for any given fault condition should decrease towards the point of supply, and the authors stress the advantage of selecting the relay current settings with this object. In other words, the effective current-transformer ratio at any point is adjusted as closely as possible to the optimum value for the requirements of the protective system. It is obvious, therefore, that the nominal ratio of the protective current transformers on a network protected by inverse-time relays ought to be determined on this basis. Unfortunately, this is a counsel of perfection, since it is generally found that such protective installations have to be applied to existing networks, on which it is inconvenient or impracticable to change the current transformers; but the point is one which should not be overlooked in the development of a protective scheme incorporating relays of this type. It also constitutes a further argument against the unsatisfactory practice of using the same current transformers for both metering and protective purposes; since metering, in general, demands the lowest possible ratio consistent with the requisite overcurrent factor, whereas protective current transformers, as the paper shows, may in certain cases require an effective ratio somewhat higher than that corresponding with normal load conditions

It seems that the definition and the example of pick-up current on page 113 are not very happily associated. The authors are presumably referring throughout the paper to relays of the type whose characteristics are shown in Fig. 1; in which case the P.S.M. value of 1·3 represents the starting-point of the calibration curve on the relay dial-plate, and not "the current at which the relay starts to move." This latter value is actually just above the setting current. The authors are, of course, at liberty to use any reasonable values for purposes of illustration; but, in quoting the figure of 6·5 amp. in connection with a 5-amp. relay, they unfortunately lend credence to a common, but erroneous, supposition that the starting current of relays of this type is always 1·3 times the nominal setting current.

The section of the master diagram reproduced in Fig. 12 does not show the symbols, mentioned in the text, indicating the types of relay installed at the various switching points; and no reference is made to the loads on the various substations. Such information is necessary to ensure that the relay current settings are sufficiently high to cover ordinary load conditions, and should be embodied in the master diagram.

Mr. R. B. Rowson: This paper is useful as it puts on record what I understood to be the usual method of calculating relay settings. I do not think that the authors' assumption that settings are always calculated on the hypothesis that the P.S.M. is in the region of 18 or more is correct. In certain cases, however, owing to the use of current transformers of too small a ratio, etc., it is not possible to take advantage of the inverse characteristic of the relay curve. For this reason the manufacturers of relays are usually conservative in their claims as to the number of relays which may be operated in series. If the possibility of grading had not been generally recognized it is difficult to appreciate why the shape of the relay characteristic was altered from what was, in effect, two lines at right angles, to a curve in which the minimum length possible is parallel to the axes.

I am glad that the authors agree that it is necessary to take resistance into account when calculating the fault currents. Most textbooks seem to suggest that resistance may be ignored, but this is certainly not true for overhead-line systems of 11 kV and below.

The very considerable labour entailed in calculating relay settings may be somewhat reduced by making an additional slide to run in the grooves of the normal slide-rule. The scaling for the additional slide is shown in Fig. D. It will be noted that the additional slide is inserted in the right-hand end of the rule, and butts against the right-hand end of the existing slide. The scale shown is for a 2-sec. inverse-time type relay, and appropriate scales may be made for other types. In use the P.S.M. which has been calculated is set against 10 on Scale D. The figure on Scale D below 10 on Scale C is the time of operation with a time setting of unity. The time for any other time setting can then be read directly in the usual manner.

Mr. P. d'E. Stowell: The paper sets out a method of obtaining the best possible performance from the widely used inverse-time overload relay (I am sorry that the authors do not use the more modern and more accurate expression " overcurrent relay "). I applied this method with excellent results some years ago to a network in which a large number of substations were operating in series and on which the maximum time setting of the relays at the input source was severely restricted on account of other considerations.

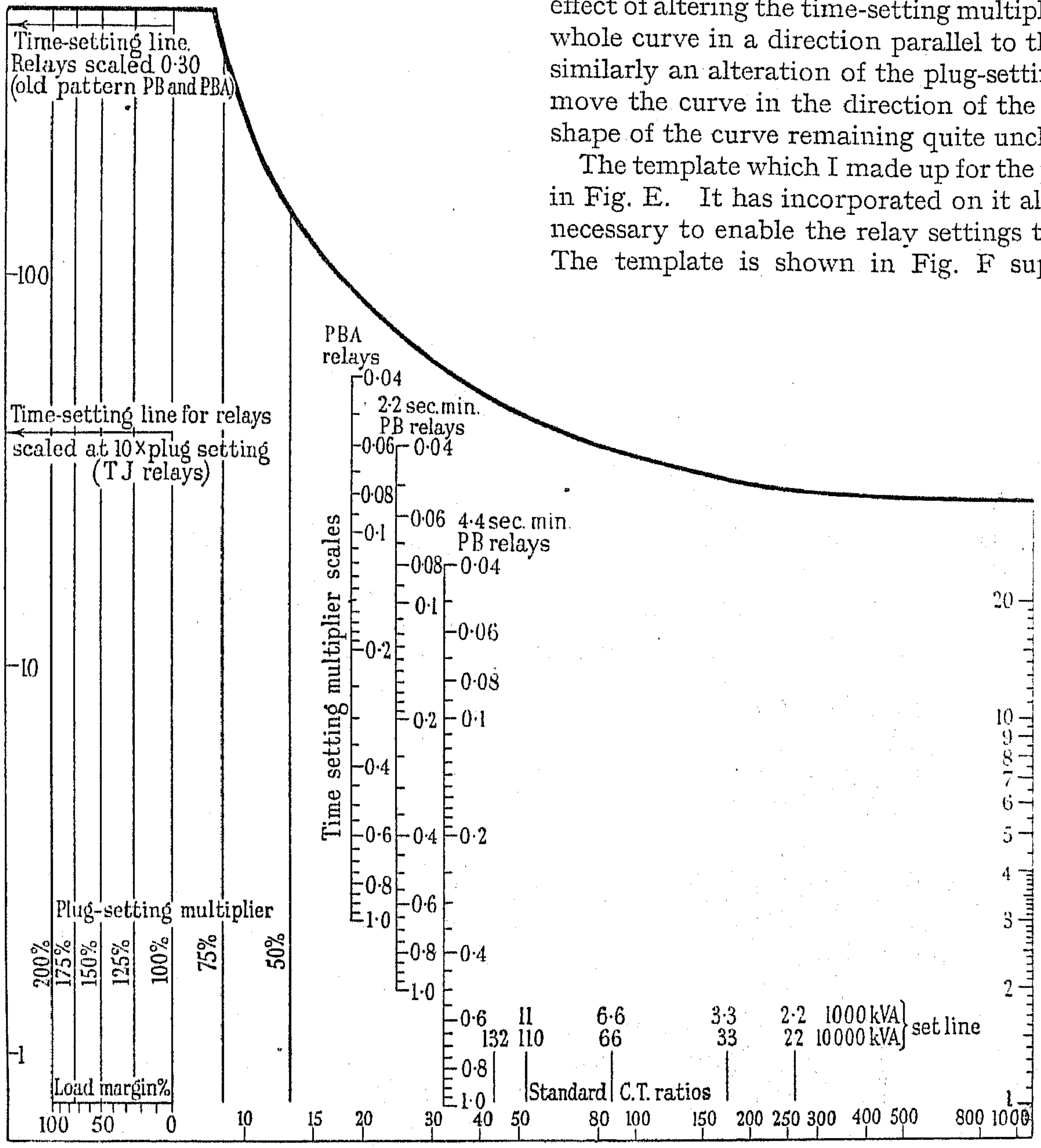

Fig. E

I do not agree with the authors' use of the term " plug-setting method " to describe the system, because it is really dependent upon the ratio (Short-circuit current)/(Normal load current) being less than 20 to 1 (approximately), at which the relay tends to saturation. In a large number of networks this ratio is often considerably less than 20 to 1, particularly where overhead transmission is employed, and in such cases this type of overcurrent protection is widely used owing to the expense of providing pilots for the balanced systems.

As pointed out in the paper, the calculations for determining the settings tend to be somewhat tedious if done in the ordinary way; but it is possible to make a template by which the required settings can be readily ascertained.

Since the effect of both the relay adjustments is to multiply the time/current curve by a quantity dependent upon the settings, the curve can be plotted on logarithmic axes with considerable advantage. If this is done, the effect of altering the time-setting multiplier is to move the whole curve in a direction parallel to the time axis, and similarly an alteration of the plug-setting multiplier will move the curve in the direction of the current axis, the shape of the curve remaining quite unchanged.

The template which I made up for the purpose is shown in Fig. E. It has incorporated on it all the information necessary to enable the relay settings to be ascertained. The template is shown in Fig. F superimposed on a logarithmic chart. The method of operation is as follows:—

A is the assumed maximum load (80 amp.) on the circuit to be protected. This is plotted against the corresponding MVA for the circuit voltage.

B is the load margin (60 %). This gives the percentage increase in load which is permissible without operating the relay. It is read on the scale on the template.

These two taken together determine the horizontal position of the template.

C is the current-transformer primary rating (100 A), assuming, of course, that the secondary is wound for the same current as the relay.

D is then the current plug-setting multiplier (125 %) to give the desired load margin (B) over the load current (A) with the current transformers (C). It is read on the template against the current-transformer primary current.

At this stage it may be necessary to adjust the horizontal position of the template in order to bring a possible plug setting into line with the current-transformer primary current.

E is a particular value of short-circuit (100 MVA)—usually the maximum which can flow in the circuit—at which F is the time of operation (0·8 sec.) of the relay required at the fault current represented by E.

The point given by the co-ordinates E and F on the chart is the one through which the operation curve is required to pass, and the template is adjusted by a vertical movement until it passes through this point.

The correct time-setting multiplier to give this result is then read off directly in one or other of the following ways, depending on the type of relay in use.

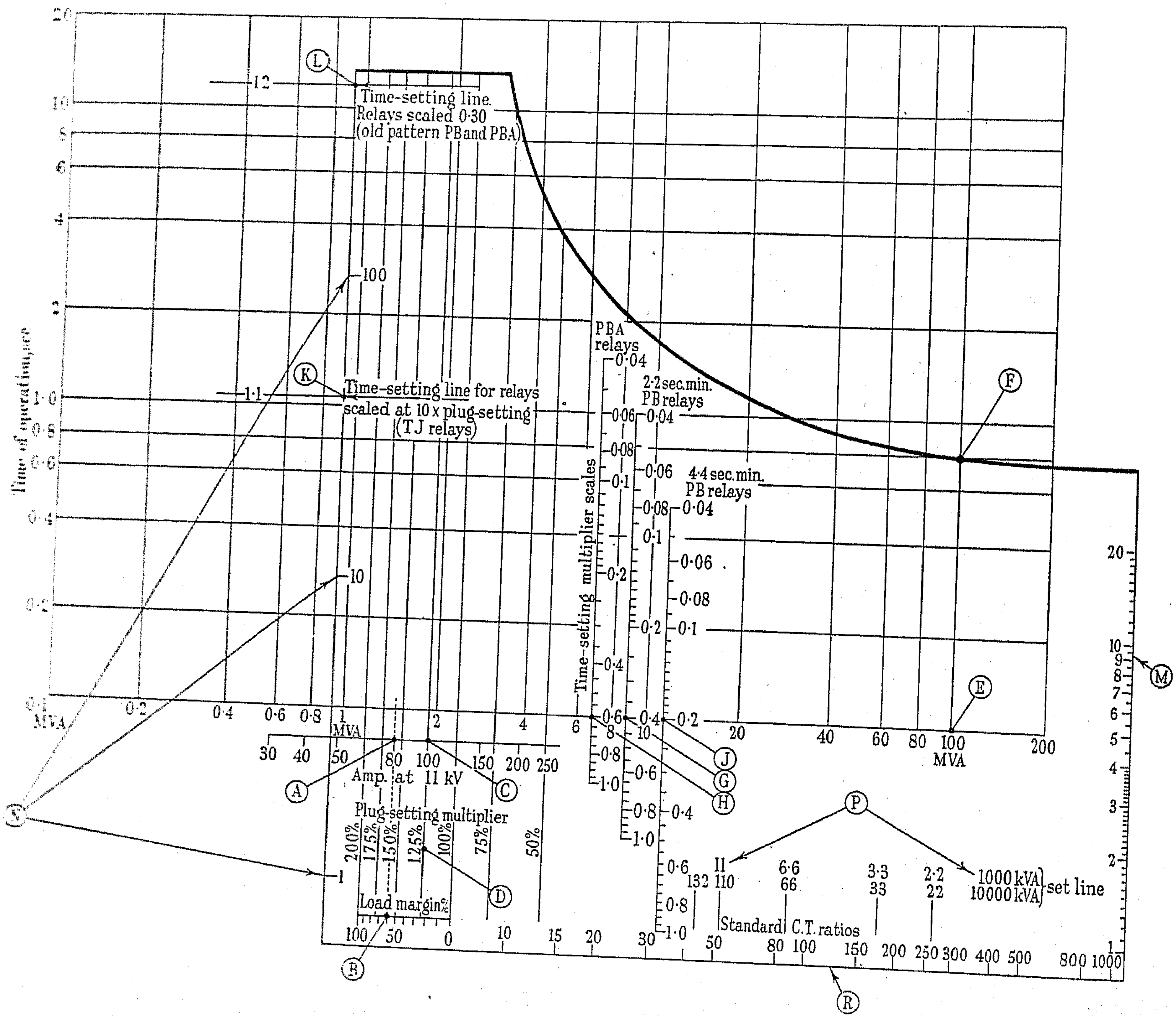

Fig. F

G is the setting (0·4) for the ordinary-type relay having a nominal definite minimum time of 2·2 sec. when set at 1·0.

H is the setting (0·6) if one of the relays of low volt-ampere rating is in use.

J is the setting (0·2) for a relay having a longer nominal definite minimum time of 4·4 sec.

In each case these settings are read off on the template against the 0·1-sec. line on the chart. On the other hand:—

K is the corresponding time setting (1·1) for a relay having a time setting scaled in seconds, when the current is 10 times the plug-setting value, and

L is the time setting (12) for the old-pattern relays which are scaled in seconds with a current 30 % over the plug-setting value.

In these two cases the setting is read off on the chart against the appropriate line marked on the template.

Though Fig. F shows the template superimposed on a logarithmic chart for clarity of description, it is not necessary in practice to have the chart, as the distances can be measured from two rectangular axes by means of suitable logarithmic scales which, for convenience, are engraved on the edges of the template thus:—

M is a scale which, together with the marks N, enables the time and MVA positions to be located; and Scale R gives the British Standard current-transformer primary currents, which can be readily located relative to the MVA scale by setting the circuit-voltage mark (as given on Scale P) against the appropriate MVA line.

The method of using the template in practice is shown in Fig. G, which is drawn for the circuit details and relay settings given in Fig. 5(*a*) of the paper. This shows how easily the time of operation of any relay with any value of fault current can be read off and the discrimination times between any pair of relays obtained.

The template shows clearly what varied means are employed for calibrating the time setting of the relay. This causes considerable inconvenience in practice on a large network where all types and makes of relay are in use, as in order to make use of any record of the relay settings as such it is also necessary to record the type of relay; otherwise the record is meaningless.

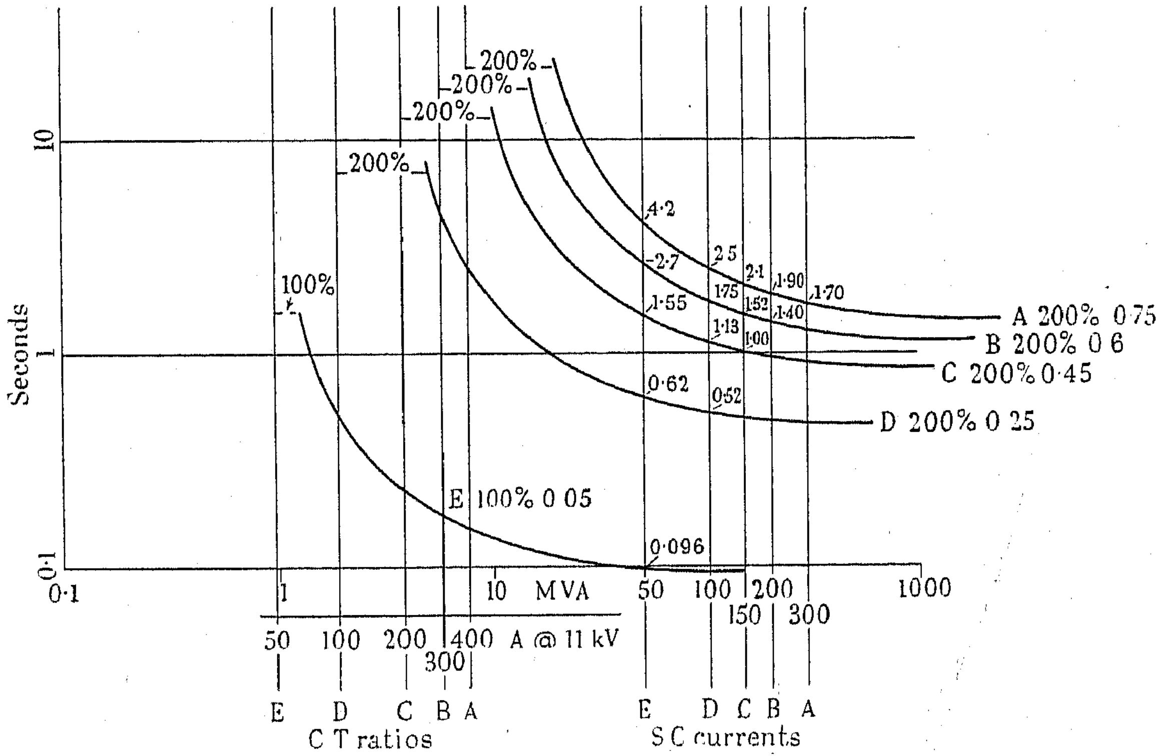

Fig. G

The multiplier method is undoubtedly a great advance over the older method of scaling the adjustment at 30 % over plug-setting current, and is far the most logical. Equally, the method of giving the time at 10 times plug-setting value is deprecated, and also in the case of relays of the low volt-ampere rating and long time-delay types, the normal curve should be used with the time-setting multiplier scaled to 0·66 and 2·0 respectively. It is earnestly suggested that the British Standards Institution should devise a standard method when B.S. No. 142—1927 next comes up for revision.

Mr. C. R. Taylor: To grade relays on the basis of time setting only is to invite trouble. The method outlined in the paper is undoubtedly an improvement on this, but disregards several important factors. It is possible to measure these factors, and allowance may be made for them when setting the relays. The figure of 0·5 sec. is given for the difference in timing between successive relays. This figure can probably be reduced considerably if the conditions are known accurately.

As regards the time of operation of the oil circuit-breaker, the time elapsing between the closing of the relay contacts and the separating of the main contacts may vary between 0·05 sec. and 0·25 sec. or longer, according to the type of switch. This time-lag may be measured using a cycle-counter, and is very consistent for any one switch.

The question of overswing of the relay is only one of many relay troubles, and is probably of little importance in a well-designed modern relay. The relay should be carefully calibrated both before being energized and at frequent intervals afterwards. A cracked jewel can make a remarkable difference to the relay characteristic.

The problem of current-transformer errors is a matter of paramount importance. A current transformer operating a relay under fault conditions is seriously overloaded. Thus, a relay may absorb 3 VA at normal full-load current, and wiring, ammeter, etc., may absorb a further 3 VA. A fault amounting to 10 times full-load current will impose a burden of 600 VA on the current transformer. The normal rating of a protective current transformer is between 5 and 50 VA. If the iron of the current transformer approaches saturation, the wave form of the secondary current is adversely affected, and this again increases the time of operation of the relay. In actual practice it is sometimes impossible to "saturate" the relay, whatever the primary current. The testing of the combination of current-transformer wiring and relay is clearly of primary importance. Practically, it is a matter of considerable difficulty, as it normally has to be done on site. The practice of providing current transformers with test windings is becoming increasingly general, and this greatly facilitates testing. None the less, some method of predicting the current-transformer characteristic from the fundamental data would be most useful, and I should like to know whether such exists.

It should be remembered that the fault current is superposed on the load current which happens to be flowing. This must be taken into account, as otherwise a fault on a lightly loaded feeder might trip out a more heavily loaded circuit.

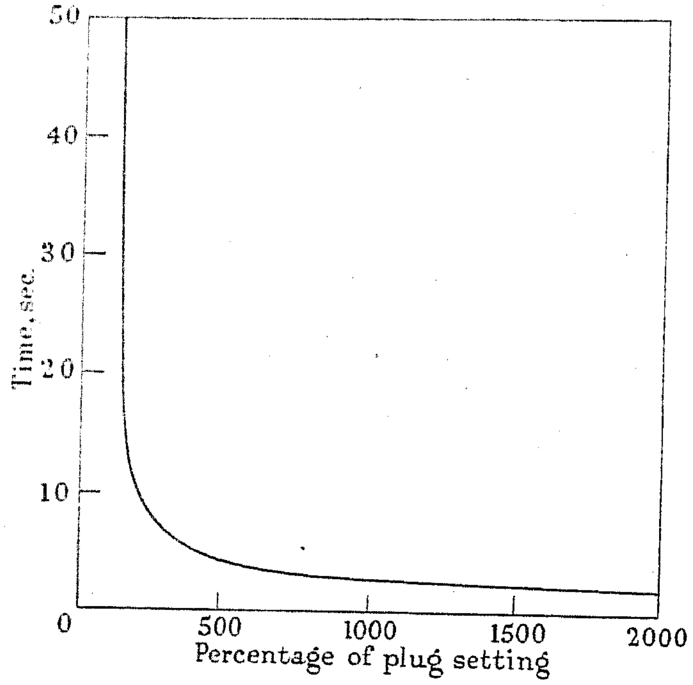

Fig. H.—Characteristic curve of relay.

The following method of checking relay settings covers the points mentioned above and appears to give satisfactory results: The characteristic curve of the relay is obtained from test results (Fig. H). Curves are obtained giving the relation between the current-transformer primary and secondary currents for various relay settings (Fig. J). These are combined to give a curve showing the relation between primary current and relay time at the relay settings tentatively chosen (Curve A, Fig. K). A curve is obtained by raising this an amount equal to the time-delay of the switch (Curve B, Fig. K), and a further curve by stepping Curve C back an amount equal to the maximum load current on the switch (Curve C, Fig. K).

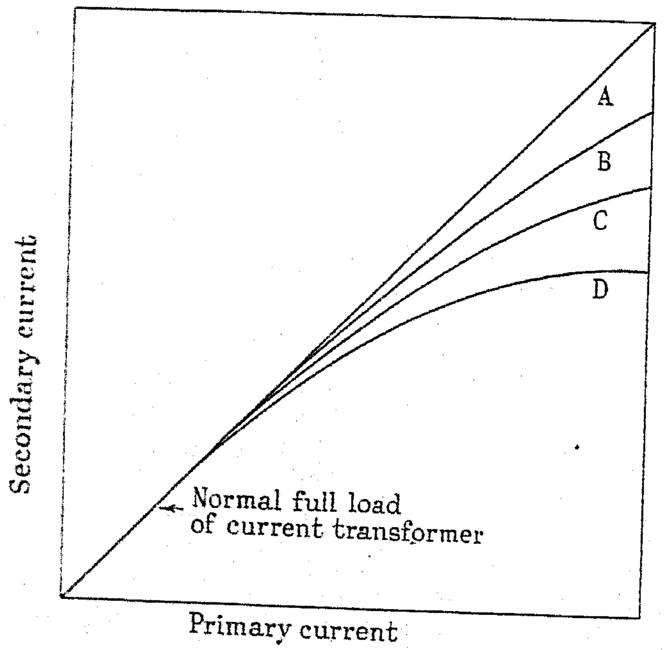

Fig. J

Curve A.—Theoretical curve for the current transformer.
Curve B.—Relay setting 200 %, 1·5 ohms.
Curve C.—Relay setting 100 %, 3·0 ohms.
Curve D.—Relay setting 50 %, 6·0 ohms.

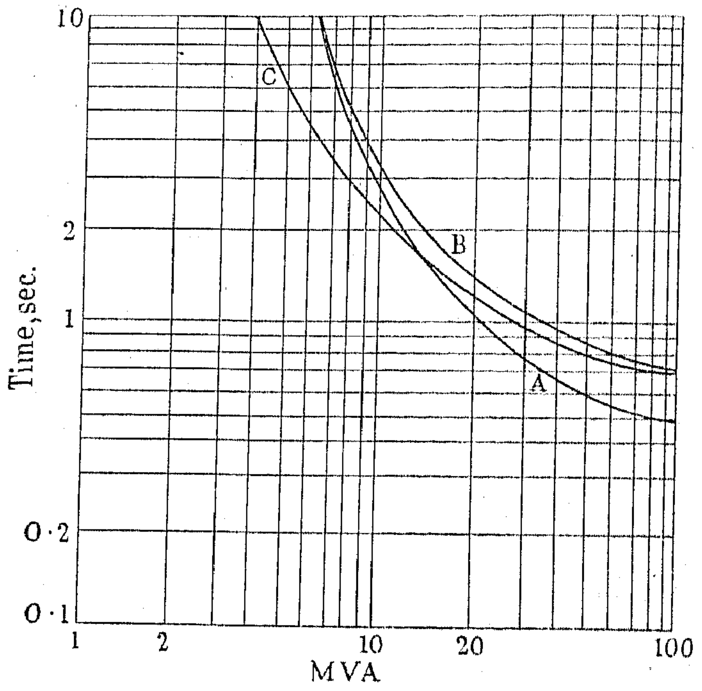

Fig. K

Curve A.—Overall characteristic of relay and current transformer at the settings selected.
Curve B.—Allowing for time-delay in the switch.
Curve C.—Allowing for maximum load current.

The area bounded by the three curves should be unique to the relay in question, as described below.

The setting of the last, and possibly also the first, relay of a series will generally be determined by external considerations. Optimum discrimination will be obtained when the " bands " produced as above are evenly spaced between the two extremes. There is risk of simultaneous operation if two bands coincide at any point. Examples of good and bad discrimination are shown in Fig. L.

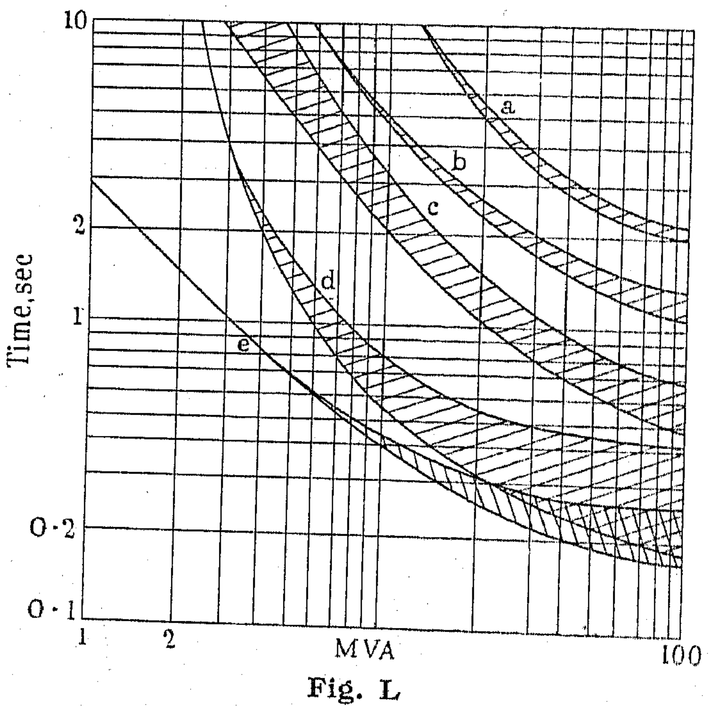

Fig. L

Discrimination between switches *a*, *b*, *c* and *d* is satisfactory. Switches *d* and *e* will trip simultaneously under heavy fault conditions.

Two practical considerations facilitate the work.

Using logarithmic-scaled tracing paper gives more evenly spaced curves and enables them to be compared directly. If the abscissae are scaled in MVA instead of amperes, the timing of switches operating at different voltages may be compared, but discretion should be exercised when doing this. No purpose is served by comparing curves at values greater than the maximum fault current available at the switch, and this point should be indicated on the diagram.

Many systems use different types of protection on one circuit. The curves of relays of the same type vary to some degree. Different current transformers exhibit very different characteristics. All these facts limit the utility of the method described in the paper. The method outlined above can readily be extended to cover all types of overcurrent protection. In a heterogeneous system it may prove impossible to avoid coincidence of the bands to some extent. Even in these cases it can often be arranged that satisfactory discrimination is obtained at the values of fault current most likely to occur.

There are several points in the paper which require elucidation. Firstly, the authors speak of protecting apparatus against sustained overload by using inverse time relays. It should be appreciated that only in special cases is it possible to protect plant against overloads and obtain discriminative protection against fault with the same overcurrent relay. Secondly, under the heading "Selection of Plug Setting" the authors say that the relay should be set to operate at minimum time for a fault at its own end of the feeder. This is frequently impossible, as is shown in the following example.

Consider a 5 000-kVA 33/11-kV transformer, impedance 7 %, fed from a source having a fault capacity of 200 MVA. On the 11 000-volt side, the relay would be set for 125 % (current-transformer ratio 250/5) to obtain full benefit from the transformer overload capacity. The primary current required to saturate the relay at this setting is of the order of 5 000 amp. The maximum short-circuit current available at the point is approximately 2 750 amp. Thus it is impossible to saturate the relay in question.

The setting of relays connected in the "residual" position for earth-leakage protection is one of particular difficulty. At a low setting such a relay offers a path of comparatively high impedance, and is shunted by two alternative paths. Thus, not only does the current-transformer ratio suffer owing to overloading, but an appreciable proportion of the residual current by-passes the relay (Fig. M). In one particular instance the effective protection obtained with various current plug settings was as follows:—

Relay plug setting	10 %	20 %	30 %
Effective protection with one current transformer ..	54 %	50 %	55 %
Effective protection with two current transformers in series	40 %	40 %	44 %

The actual values will, of course, vary with the types of relay and current transformer used, but the case is fairly typical. It will be seen that a reduction in the current setting may result in an increase in the relay operating time with an earth fault of given magnitude. In general, it is clear that the degree of protection obtained is very much smaller than might be expected.

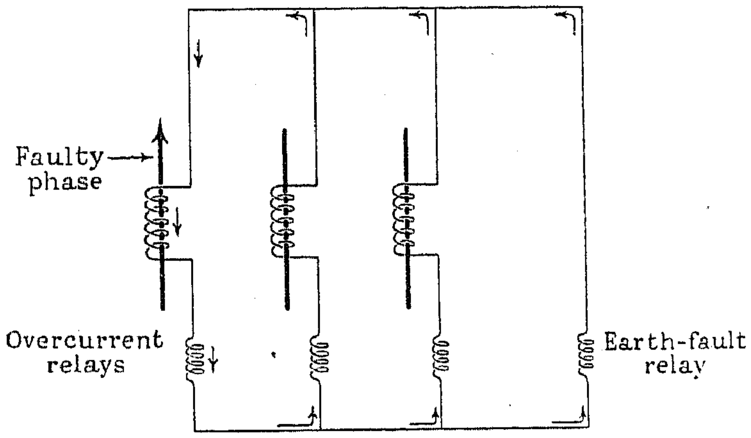

Fig. M.—Earth-leakage relay, showing existence of paths in parallel with the relay.

Accurate knowledge of the factors involved is required for the grading of relays. Still more important, however, is the question of overall testing of the protective system on site. Troubles may develop both in the course of manufacture and in service, and the testing of component parts may fail to discover them. No amount of calibration can rectify an incorrect or faulty connection.

[The authors' reply to this discussion will be found on page **133**.]

DISCUSSION BEFORE THE NORTH-WESTERN CENTRE, AT MANCHESTER, 23RD JANUARY, 1940, ON THE ABOVE PAPER*

Mr. C. Ryder: In this paper the authors deal particularly with the application of protective relays and the development of protective schemes. I notice that they use the generally accepted grading interval of 0·5 sec. on the definite minimum part of the curve in determining their time-multiplier settings. I should like to ask whether they have considered using a smaller figure, or whether they have found that this figure is the minimum it is advisable to work to in practice.

It would be interesting if the authors would give their experience with regard to the maintenance of relays on such a network as the one they have described, and the record of faulty operations with which they have had to contend.

I am rather disappointed to find such a small paragraph relating to overswing, as I consider this to be an important point in overcurrent induction-type relay application and design. It is of importance in application because it may easily become the controlling factor in the determination of the discriminating tolerance between adjacent substations. Recent improvements in circuit-breaker design are such that both tripping and arcing times have been considerably reduced, and it is essential that relay design should maintain its present high standard in order that supply authorities may obtain the full benefit of any reduction in the time required for fault clearance.

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* The paper by Mr. J. R. Brookman, entitled "Maintenance of Relays and Associated Equipment," was also read and discussed at this meeting and will be published, together with the discussion relating thereto, in a later issue of the *Journal*.

As far as relay design is concerned, a certain amount of overswing is inevitable, since the movement, when set in motion by the fault current, possesses kinetic energy which must be dissipated before it can be brought to rest and returned to its initial position by the restoring torque. The problem therefore is to arrest the motion of the movement in the shortest possible time from the instant the fault current is interrupted, so as to obtain the minimum of interference with the discriminating properties of the relay. Since the kinetic energy is given by $\frac{1}{2}I\omega^2$ it is apparent that a low-velocity light-weight movement is required, and the relay previously illustrated has been designed with these objects in view.

TABLE A

TABULAR METHOD OF DETERMINING T.M.S. AND P.S.M. VALUES FOR TIME-GRADED OVERCURRENT PROTECTION

Relay at		A. C.T. 200/5. Plug setting 100				B. C.T. 150/5. Plug setting 100				C. C.T. 100/5. Plug setting 150				D. C.T. 200/5. Plug setting 50			
Fault at	I_F	P.S.M.	T.M.	T.M.S.	D.M.T.	P.S.M.	T.M.	T.M.S.	D.M.T.	P.S.M.	T.M.	T.M.S.	D.M.T.	P.S.M.	T.M.	T.M.S.	D.M.T.
Substation A	2 000	10	2·9	0·36	1·04												
Substation B	1 400	7	3·5	0·36	1·27	9·35	3	0·255	0·77								
Substation C	800	4	5	0·36	1·8	5·35	4	0·255	1·02	5·35	4	0·126	0·51				
Substation D	500	2·5	7·6	0·36	2·74	3·33	5·8	0·255	1·43	3·33	5·8	0·126	0·73	5·0	4·2	0·05	0·21

I_F = fault current, in amp. P.S.M. = plug-setting multiplier. T.M. = time (sec.) at unity T.M.S. T.M.S. = time-multiplier setting. D.M.T. = definite minimum time, in sec.

Mr. S. R. Mellonie: With regard to the question of damage to cables, I suggest that there is some margin over and above that given by the authors. I have checked the curve they quote from the paper by Messrs. Clothier, Leeson and Leyburn and find that it corresponds to a rise of only 60 deg. C. I think that paper-insulated cables will stand a much higher temperature than this for short periods. I would draw attention to the fact that B.S. No. 81—1936 allows a rise of 150 deg. C. for periods up to 5 sec.; and further, in a paper* published as long ago as October, 1934, it was suggested that the total temperature can be 250° C. It therefore appears that some margin exists.

Mr. M. Kaufmann: The system known as time-graded protection is one of the simplest in principle and also the cheapest to buy, but it is the most difficult to apply. The expressions "plug-setting method" and "saturation method" are new to me, and I wonder by what process of reasoning the authors have arrived at them. I think a better name for those two methods would be "scientific" and "rough and ready." Even that description is hardly correct, however, because, although the authors confine themselves to overcurrent as distinct from earth-fault protection, the chances of relays not being called upon to operate on the saturated portion of their characteristic are rather slight, especially now that it is the general practice to earth systems solidly and at the same time to insist on using relays with a minimum setting of 10 %. For example, there is a case within my own experience in which the fault current was 7 000 amp., the current-transformer ratio 30/5 and the relay setting 50 %, giving a P.S.M. of 7 000/15 = 466.

I would point out that there are certain drawbacks to the plug-setting method.

In the case the authors have chosen, the current transformers are a more than usually heterogeneous collection. There are current transformers of ratio 50 : 5 at one end of a feeder and current transformers of ratio 150 : 5 at the other, although the same load is carried at both ends.

Referring to the ring-main system which is the basis of Fig. 6, the north line is a relatively short one, judging by the current it passes compared with the southern circuit. If the north line is put out of action all the load must travel by way of the south line, in which case there is a danger of passing 150 amp. through the 50/5-amp. current transformer at Substation 4, Switch 1. This will cause serious overheating of the current transformers.

The authors seem to have confined their attention to the case of maximum short-circuit kVA, but the minimum must also be kept in mind. It may be that in their case 360 MVA is the minimum, but if not there is a danger that some of the relays may not operate, especially if a factor not mentioned in the paper, namely "decrement factor," is taken into account. They do indicate that the main substation is fed by the grid, and that would tend to reduce the decrement and to maintain a high fault current. There are cases on record where relays with even lower settings than those used by the authors failed to operate, owing to the severe decrement of the fault current.

The method of applying time-graded overcurrent relays with which I am familiar is not only somewhat less lengthy than that of the authors but also automatically takes into account the effect of the "plug-setting multiplier." The method, which may be called the "tabular" as opposed to the "diagrammatic" method of the authors, is illustrated in Table A. The points to be noted are (*a*) that since the condition of maximum kVA is the most arduous from the point of view of discrimination, the "open-ring" condition only need be considered (this shortens the work); (*b*) the plug setting of the lowest-timed relay tends to be automatically fixed by the need to reduce the operating time of that relay to the lowest value possible (this inevitably influences the plug settings of the remainder of the relays in the chain); (*c*) the "discriminating" time-interval is seen at a glance for all relays for a fault at any substation, as well as all other relevant data such as current-transformer ratio, fault current, definite minimum time-setting, and plug-setting multiplier. Table A shows the grading in the clockwise direction round the open ring; a similar table is required for the counter-clockwise direction.

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* V. M. MONTSINGER and W. M. DANN: *Electrical Engineering*, 1934, 53, p. 1353.

The conclusion to be drawn from the paper is that the grading of overcurrent-relay current settings as well as of the time settings has decided advantages when the fault currents are not such as to operate the relays on the definite minimum (or saturated) portion of their time/current characteristic. A judicious choice of current settings helps to prevent the operating point from reaching the saturated portion, but the freedom of choice is rather more limited than the paper would lead one to suppose, owing to the risk incurred in adopting too high a current setting.

Mr. A. B. Stevenson: There appears to be a slight mistake on page 117, where the authors say "The impedance from B to the fault will be small compared with that round the loop BCF." I rather think that the impedance from B to the fault is large, as it is what limits the fault current.

The authors' main thesis is that a discriminating time of 0·5 sec. is necessary with modern circuit-breakers; but this may now be halved in view of the superior methods of arc control available.

There is a large and growing field for relay application in the protection of the h.v. networks of industrial undertakings. Large numbers of factories are changing over from direct to alternating current, and the consequent demand for suitable relays should have the serious consideration of manufacturers in order that the requirements may be met. A question arising in this connection is whether the designers could devise a method of obtaining voltage supplies for the directional relays from the 400-volt secondaries of existing transformers.

Mr. W. H. Lawes: I would inform the authors that the relay curve is scarcely affected by the saturation of the iron. The braking of the disc is due partly to the permanent magnet and partly to the a.c. flux in the gap, and at heavy overcurrents the latter predominates. The true definite minimum time is obtained by making tests without the permanent magnet.

Mr. J. Solomon: In the paper by Messrs. Clothier, Leeson and Leyburn to which the authors refer, the cable sizes are apparently based on a current density of 80 000 amp. per sq. in. for 0·5 sec. (cf. 150 000 amp. per sq. in., as recommended in B.S. No. 81—1936, Clause 18), which I believe is in accordance with C.M.A. recommendations. If, however, the figure of 120 000 amp. per sq. in. were adopted, as suggested by Mr. Haws,* then the 0·25-sq. in. cable referred to by the authors would carry a fault current of 22 500 amp. for 0·9 sec., instead of 16 600 amp. It would therefore be of interest to see similar curves to those of Fig. 10 for the current-density limits of 120 000 and 150 000 amp. per sq. in.

Mr. H. B. Dreyfus: In the paper it is pointed out that overload relays are often graded on the assumption that the fault current will exceed the saturation value of the relay, and consequently that the relay will operate in its minimum time. I hope that this state of affairs is rather the exception than the rule, because it means utilizing a relatively expensive inverse-time definite-minimum relay as a definite-time relay, which costs considerably less.

In the paragraph "Factors which Control Discrimination" (page 114) the authors show that the P.S.M.'s of successive relays should always be equal to or less than the P.S.M. of the previous relay. This is ideal and, when all the relays have the same curve, essential. It often occurs, however, that successive relays are of different manufacture, and then it is sometimes necessary to have relays with P.S.M.'s even greater than the P.S.M. of the preceding relay. This is due to the difference between the time/current curves, and as long as the time/current curves are separated by the necessary discriminating time *for the portion of the curves in use* the relays can be relied upon to discriminate correctly under all conditions. The settings have to be reviewed very carefully, however, when plant-increases are made, to ensure that the curves are not too close together for the increased maximum fault currents.

The problem of grading relays of different manufacture and different characteristics is always arising, because the relays are usually supplied by the makers of the chosen switchgear at each substation. From the point of view of relay grading, it would be much better if the relays were all supplied under one contract and were therefore of similar design and characteristics. This would simplify not only the grading of relays but also maintenance and spares problems.

In the numerical example illustrated in Fig. 5, the authors show successive switches with decreasing current-transformer ratios at stations A to E, and they set the relays at 200 % at each station except E, where 100 % setting is chosen. In practice, however, one usually has several stations, or successive oil circuit-breakers, with similar current-transformer ratios, such as 400/5, 300/5, 300/5, 300/5, 200/5, 200/5, etc., when current settings such as 200 %, 200 %, 175 %, 150 %, 200 %, 175 %, etc., have to be chosen. These settings still give decreasing current settings of 800, 600, 525, 450, 400 and 350 amp.

In commenting on Fig. 7(*m*), the authors point out that relays M and N are set for two feeders in parallel, as the substation is attended, and in the event of a feeder tripping-out the control engineer can reset the relay to a time multiplier of 0·55 in place of the normal setting of 0·45. I consider it rather dangerous, from the point of view of continuity of supply, to reset a live relay on a single circuit when that circuit is the only remaining supply. Also, the control engineer may be too busy to reset the relays, or may even forget. I would set the relays permanently at the higher setting, and not risk a false trip at a time of need.

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* *Journal I.E.E.*, 1938, **82**, p. 81.

The authors show in Fig. 7(*b*) that they check their settings for operation even on the smallest 3-phase faults. Are the settings also checked for earth faults? Earth faults are not uncommon on underground-cable systems, and nowadays we seem to be experiencing rather a large number of busbar faults, which invariably start as earth faults and do much more damage if left to develop into phase faults before being cleared by the back-up protection.

Mr. F. Mather: It would be interesting to know why the authors do not use leakage protection. My experience is that most faults on cable systems are earth faults, and several good results follow from the use of (1) a comparatively large value of earthing resistance at the neutral point, and (2) fairly low-set leakage relays. In the first place, it can be arranged that instead of coming out with a terrific shock the breaker comes out quite gently and there is far less damage to its contacts, much less carbonization of the oil and, in fact, less necessity for maintenance after faults. Furthermore, if these faults can be limited, the synchronous plant on the system does not trip off so frequently. On the system with which I am concerned the synchronous plant used to trip off when a fault occurred at the opposite end of the system, but we have now succeeded in preventing such troubles.

By limiting the earth-fault current by means of a fairly large resistance in the neutral we also reduce the damage to adjacent cables. We have had manhole covers blown into the air on the occurrence of a phase fault, but such a thing never happens with limited earth faults covered by low-set, quick-acting leakage protection.

I do not like systems which depend entirely on time grading, because in my opinion 2 sec. is far too long for a fault to stay on the system. If one has to put up with a time-graded system for reasons of cost, well and good, but such a scheme does not bear comparison with the pilot system.

With reference to Mr. Ryder's comments, I should like to say that I have tried relays with a time-grading interval of 0·45 sec., and they have operated with perfect success on two or three occasions.

[The authors' reply to this discussion will be found on page 133.]

NORTH MIDLAND CENTRE, AT LEEDS, 27TH JANUARY, 1940

Mr. W. T. J. Atkins: At first sight this paper seems to be very elementary, but a little consideration will show that although all the principles involved are simple, their actual application is distinctly complicated. Since, moreover, these governing principles should be considered not merely in relation to a pure overcurrent scheme but wherever overcurrent is used as a "back-up" to some other protective system, the suggestions made in the paper deserve careful study.

Two important implications of the paper are that fault currents rather than load currents should govern the settings of overcurrent relays, and that the fault characteristics of a system must be given very detailed attention. The arithmetical work involved is, of course, very laborious owing to the large number of possible circuit combinations, and it is distasteful to the normal engineer. He cannot, however, safely relegate this unpleasant duty to a junior, as the ultimate responsibility is his. These considerations clearly point to the moral "Don't shy at the arithmetic."

The characteristics of relays are just as important as the characteristics of faults, and standard time/current curves should not be trusted without reservation. One feature which may prove deceptive, for example, is the starting current as shown in Fig. 1. A relay of the pattern concerned is supposed to operate at a current 30 % in excess of the nominal setting, but very often it will creep at, or even below, the nominal current, with possibly disastrous consequences.

Mr. F. Gurney: One valuable feature of this paper is the attention it has drawn to the fact that those systems of distribution which are not equipped with pilot cables can still have very satisfactory methods of discriminative protection. Some of the diagrams show small networks, typical of a large number of the smaller undertakings in this country, which have no protective schemes whatever, and which would, of course, give much more reliable service if they had.

I should like to ask the authors how the scheme has operated with the relay settings given as a result of the various calculations recorded in the paper. Have the results been satisfactory from the point of view of correct switchgear operations?

The President, Mr. Johnstone Wright, in his recent Inaugural Address,* said that protective-gear operation efficiency on the C.E.B. system is in the neighbourhood of 90 %, and this is a very satisfactory figure. His statement is interesting because some years ago engineers in this country liked to dismiss the question of protective gear by saying that in the history of their particular undertaking more shutdowns had been caused by protective gear than by real troubles.

Mr. A. Kelso: The authors seem to be very fortunate in having a long time setting at the main substation. On our little undertaking we have less than half that time to deal with, and therefore difficulties in grading throughout the network are not so easily overcome as the paper indicates.

My second point is that where close discrimination (as regards time setting) between adjacent switches has to be carried out, the time of operation of the switches comes into the calculation to almost as great an extent as the relay. I should like to ask the authors whether, when grading relays, they take into consideration the time-lag between the relay operation and the opening of the circuit.

Mr. E. S. Bolton: The main point brought out in the paper is that one switch should be set to protect another in the event of the switch nearest the fault not operating. But is there not a likelihood, if one is not careful to set the switches with due allowance for time-lag, that the switch farthest away from the fault may operate instead of the switch that is most concerned? Also, I suppose the authors have taken into consideration the fact that the ratio errors of current transformers vary from 5 % to 10 % according to the type.

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* *Journal I.E.E.*, 1940, **86**, p. 1.

Finally, I should have liked the authors to mention their views on switchgear maintenance. A proper maintenance staff can not only lengthen the life of switchgear but also obviate unnecessary faults in the future.

THE AUTHORS' REPLY TO THE GENERAL DISCUSSION AND TO THE DISCUSSIONS AT MANCHESTER AND LEEDS

Messrs. J. W. Gallop and **R. H. Bousfield** (*in reply*): Several speakers have demonstrated what may be termed the template method of obtaining the required relay settings. As was pointed out by Mr. Atkins, however, the laborious calculations, referred to in the latter part of the paper, were the network calculations required. The main argument of the paper, that the plug setting can frequently be increased to advantage, should not be overlooked. Whilst we appreciate that where relays, with differing characteristics, have to be graded, the template method is almost the only one possible, we agree with Mr. Dreyfus that any protective system should be regarded as a whole and that the use of relays having differing characteristics is strongly to be deprecated.

Mr. Freeland remarks that there must be few networks where overload protection can be used for anything except back-up protection. In the Introduction to the paper it is emphasized that, even so, it is essential to ensure that the overload relays are correctly graded. We appreciate Mr. Atkins's confirmation of this point. In this connection there must be numerous rural networks where other forms of protection are virtually impossible.

We are aware that standard practice, which we assume Mr. Mather had in mind, is to use one earth-leakage and two overload relays in place of three overload relays. On the system with which we are concerned, earth-leakage protection is only installed where the loading of the network is such that the current-transformer ratios are too high to allow a reasonably high plug-setting multiplier on earth faults. This attitude allows of a relatively high plug-setting for the earth-leakage relay, as the relay nearest to the supply is graded against pure overload protection and thereby minimizes the difficulties outlined by Mr. Taylor.

We are indebted to Mr. Grieveson for his remarks concerning pick-up current. With regard to the master diagram, it has been found unnecessary to insert feeder loads, as these can usually be sufficiently memorized to check the settings. The relay settings are put on a second diagram as in Fig. 6. The reason for this is simply to keep the diagram as small and clear as possible.

Mr. de Stowell's remarks concerning the ratio of fault to full-load currents seem to contradict the impressions of other speakers. Our experience is such that where the ratio falls much below 20, excepting earth faults, regulation troubles tend to become acute. He also appears to miss the argument of the paper in the description of his template method illustrated in Fig. F, as the horizontal position of the template is fixed by the maximum load on the circuit and the permissible load margin. This fixes the P.S.M. We advocate, however, fixing the plug-setting on the basis of fault MVA and then checking that the load margin is sufficient afterwards. The method is tantamount to choosing the current-transformer ratio according to the fault current, as Mr. Grieveson has shown.

When testing circuit-breakers for time of operation, it should not be forgotten that arcing time is a very appreciable percentage of the total time of operation. It is for this reason that reduction in the accepted 0·5 sec. discriminating time suggested by Messrs. Taylor and Ryder is difficult to obtain in practice. Where manufacturers have supplied these data with their circuit-breakers, it might be done with a fair amount of confidence, otherwise it is rather a question of experiment. We notice that Mr. Mather has been successful with a discriminating time of 0·45 sec.

Mr. Taylor's question concerning current-transformer characteristics would seem to be met by the open-circuit test. A low voltage, up to about 50 volts, is injected into the secondary winding and the voltage and current readings taken. These are plotted against each other. This can only be relied upon as a comparative test, although where wave form can be checked and instrument characteristics taken account of, rough predictions can be made of the behaviour of the current transformer with various burdens. The question of taking load currents into account at the time of the fault is usually an unnecessary refinement, since the drop in voltage, along the faulty feeder, reduces the load to a negligible quantity.

With regard to Mr. Taylor's example, it is presumed that there is no circuit-breaker at the terminals of the 33-kV side of the transformer. In this case, the next relay back could presumably have a plug-setting up to 175 % on a 100/5 current transformer and still obtain a P.S.M. of about 19. The effect of the transformer is then merely to add impedance to the transmission line, which would considerably assist grading with the 11-kV relay. The fact that the latter is not on saturation is immaterial, as the 33-kV relay will be for a fault on its own system.

In reply to Mr. Ryder's and Mr. Gurney's queries concerning the operation of the system: for the year ended December, 1939, the whole system had 63 disturbances involving 101 relay operations. Of these, 99 were correct and of the 2 failures neither was due to faulty relays or relay operation. It has been found in practice that this type of relay requires the minimum of maintenance, and little has been done other than periodic inspection.

Messrs. Mellonie and Solomon raise queries concerning the curve reproduced in Fig. 10. We submit in Fig. N further curves taken recently from the *Electrical Power Engineer* (October, 1939) and *Distribution* (January, 1940), and also the 150 000-amp./sq. in. and 120 000-

amp./sq. in. curves. Those given in the paper by Messrs. Clothier, Leeson and Leyburn, are reproduced in the same manner for comparison. None of these authorities gives the basis upon which the curves have been calculated, and it seems difficult to reconcile them with Messrs. Mellonie and Solomon's calculations. From the recent date of these publications, we assume that they must be in possession of some improved temperature/time formula.

Concerning Mr. Kaufmann's remarks, the terms "saturation" and "plug-setting method" are our own invention and were merely introduced to facilitate description. That the saturation method exists can be evinced by the following quotations from an instruction book describing the grading of these relays: "For phase-fault relays, the maximum short-circuit current may usually be assumed to be not less than 20 times the value represented by the relay current-setting chosen unless careful calculation shows it to be lower."

Again—"If the feeders are in the form of ring mains it is not permissible to grade the current settings unless the current-transformer ratios differ, in which case the differences must be compensated for in the settings."

This is in direct contradiction to the plug-setting method, the only reference to which occurs at the end of the pamphlet, where it describes how to grade relays where the P.S.M. is below 20. As far as we are aware there is no literature which suggests deliberately lowering the P.S.M. in order to reduce the value of T_m.

With reference to the "heterogeneous collection of current transformers," this was brought about by the fact that the circuit-breakers at substation 1 (Fig. 6) had recently been renewed and the current transformers chosen to cope with future load. In addition, in our opinion protective current-transformer ratios should increase towards the point of supply, where fault MVA are higher, and should be selected primarily on a fault-MVA basis, the load being a secondary (although necessary where it is large) consideration. This view is supported by Mr. Grieveson. We would suggest that the 30/5 current-transformer working on a fault current of 7 000 amperes, unless used for metering purposes only, was a case of bad design.

We are grateful to Mr. Kaufmann for calling attention to the need for considering the case of minimum fault MVA. Its effect is readily assessed by examination of the fault-current diagrams, when the effect of, say, halving the P.S.M. can be seen at a glance. It is in this connection that the diagrammatic method has an advantage over that described by Mr. Kaufmann, as it enables the effect to be seen under the most onerous conditions, namely with the ring closed. This latter condition may well halve the P.S.M.'s obtained with the ring open, and is, after all, the condition for normal operation.

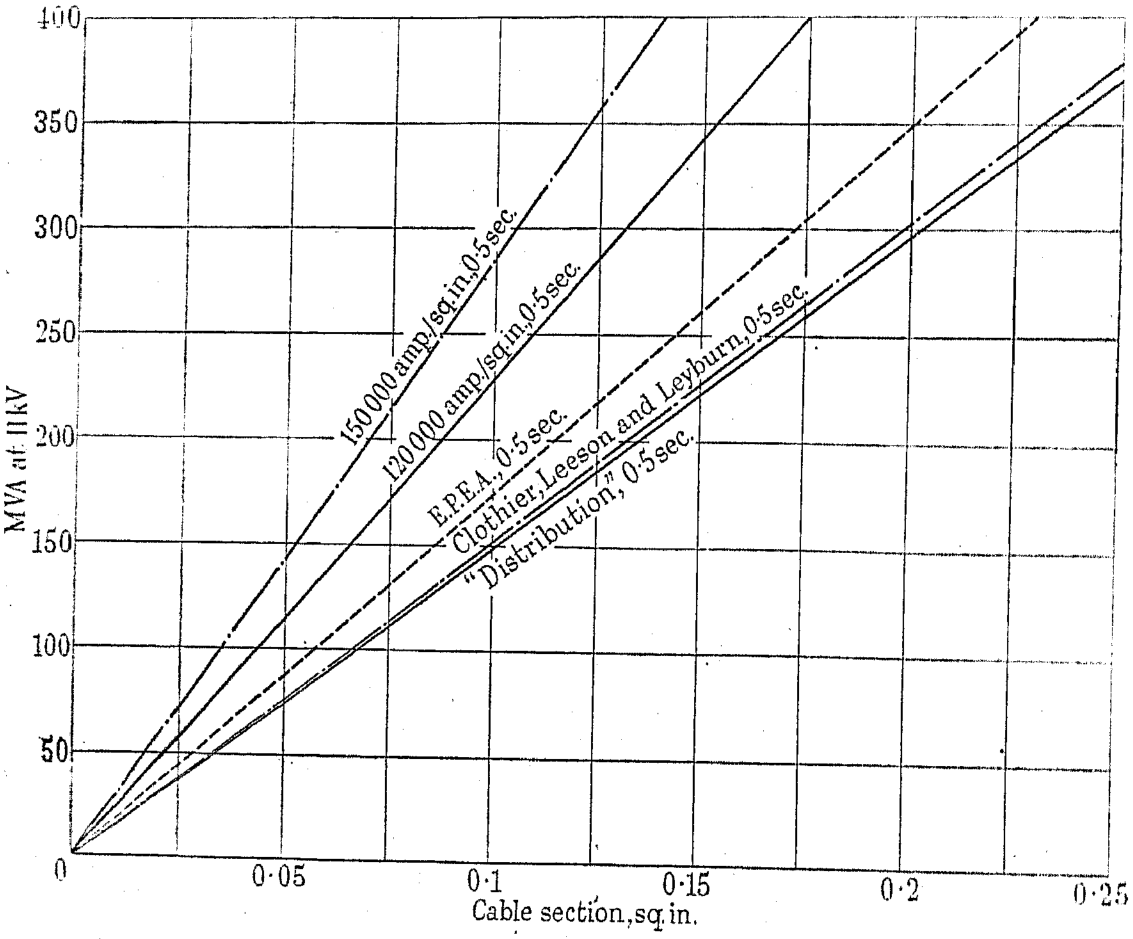

Fig. N

We are indebted to Mr. Solomon for his correction.

The question raised by Mr. Dreyfus concerning emergency settings depends on local conditions. The case quoted in the paper, however, involves raising the time multiplier, and the danger of tripping the relay is thus remote.

Apparently Mr. Stevenson has misunderstood Fig. 9, where the fault F is assumed to be at the tail box of the circuit-breaker at 6. As the busbars are at B, the impedance from B to F will be negligible. It is the impedance between A and B that limits the fault current.

REFLECTION CURVES AND PROPAGATION CHARACTERISTICS OF RADIO WAVES ALONG THE EARTH'S SURFACE*

By J. S. McPETRIE, Ph.D., D.Sc., Associate Member, and Miss A. C. STICKLAND, M.Sc.

(*Paper received* 6*th May*, 1939, *and read before the* WIRELESS SECTION 3*rd April*, 1940.)

SUMMARY

The paper contains curves from which the reflection coefficient at the earth's surface for radio waves of any state of polarization can be determined for angles of incidence greater than 80°. It is pointed out that the ray theory, on which the reflection from a reflector is assumed to be equal to the radiation from an image of the transmitting aerial in the reflecting surface, is not applicable at grazing incidence unless the heights of the transmitting and receiving aerials are comparable with the wavelength. From an analysis given by Norton, however, it is deduced that, when the ray theory does not apply, the field at the receiver is equal in most practical cases to the vector addition of two fields, one that given by the ray theory, and the other, which corresponds to the Sommerfeld surface wave, having a magnitude dependent on the electrical properties of the reflector and the distance between transmitter and receiver but independent of the heights of transmitter and receiver. The ratio of the magnitudes of the surface wave to image fields is much less for horizontally than for vertically polarized waves, so that the ray theory is applicable over a wider range of angles of incidence for horizontally than for vertically polarized waves.

INTRODUCTION

A method[1] has been described recently by means of which the reflection coefficient of the ground for radio waves can readily be determined from a series of curves for angles of incidence up to 80°. This method has proved so convenient that it was decided to extend it to include larger angles of incidence because they correspond to one of the most important problems in radio-communication, namely the propagation of radio waves along the earth's surface. The analysis of the propagation of radio waves is extremely complicated when the transmitter and the receiver are near the ground, and some notes are given in the paper to indicate how the field at the receiver may be calculated under such conditions of large angles of incidence.

FRESNEL REFLECTION COEFFICIENTS

The radiation reflected from the ground may have any state of polarization, but it can usually be resolved into two linearly polarized components. It is most convenient to resolve the radiation into the two components having the electric vector polarized in, and perpendicular to, the plane of incidence. Radio engineers are accustomed to refer to these two components as vertically and horizontally polarized† respectively. This latter nomenclature will be used throughout the present paper. Both the vertically and the horizontally polarized components of the radiation incident on the ground are reflected with change in amplitude and phase, i.e. the reflection coefficient is complex and may be represented in the form

$$R = K + jK'$$

in which $\sqrt{(K^2 + K'^2)}$ is the magnitude of the reflection coefficient and arc tan K'/K is the advance of phase on reflection.

The reflection coefficients for vertically and horizontally polarized waves are respectively

$$R_v = (K_i + jK_i')$$
$$= \frac{\left[\kappa - 2j(\sigma/f)\right]\cos\theta - \sqrt{\left[\kappa - 2j(\sigma/f) - \sin^2\theta\right]}}{\left[\kappa - 2j(\sigma/f)\right]\cos\theta + \sqrt{\left[\kappa - 2j(\sigma/f) - \sin^2\theta\right]}} \quad (1)$$

and

$$R_h = (K_p + jK_p') = \frac{\cos\theta - \sqrt{\left[\kappa - 2j(\sigma/f) - \sin^2\theta\right]}}{\cos\theta + \sqrt{\left[\kappa - 2j(\sigma/f) - \sin^2\theta\right]}} \quad (2)$$

in which κ and σ are the dielectric constant and the conductivity (in electrostatic units) of the reflecting medium for radiation of frequency f, and θ is the angle of incidence.

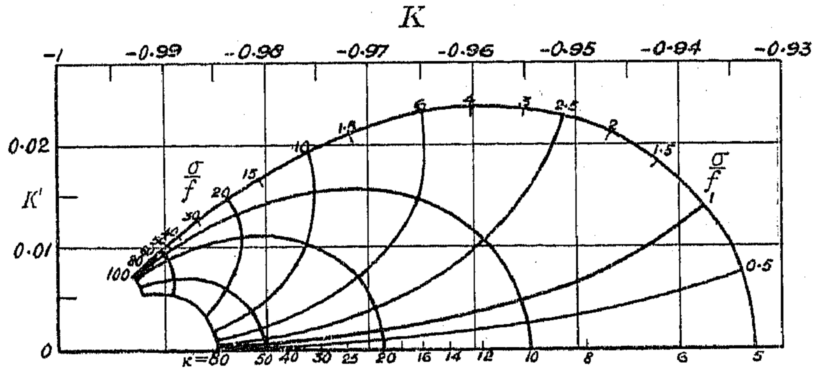

Fig. 1.—Curves giving in-phase (K) and in-quadrature (K') components of the reflection coefficient for a given angle of incidence and various values of ground constants.

For computation purposes it is necessary to determine the two components K and K' of each reflection coefficient. They are

$$K_i = \frac{\left[\kappa^2 + 4(\sigma^2/f^2)\right]\cos^2\theta - (c^2 + d^2)}{\left[\kappa^2 + 4(\sigma^2/f^2)\right]\cos^2\theta + (c^2 + d^2) + 2\cos\theta\left[\kappa c - 2d(\sigma/f)\right]} \quad . \quad . \quad (3)$$

$$K_i' = \frac{-2\cos\theta\left[\kappa d + 2c(\sigma/f)\right]}{\left[\kappa^2 + 4(\sigma^2/f^2)\right]\cos^2\theta + (c^2 + d^2) + 2\cos\theta\left[\kappa c - 2d(\sigma/f)\right]} \quad . \quad . \quad (4)$$

$$K_p = \frac{\cos^2\theta - (c^2 + d^2)}{\cos^2\theta + (c^2 + d^2) + 2c\cos\theta} \quad . \quad . \quad (5)$$

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* Official communication from the National Physical Laboratory.

† In order to conform with the notation used in the earlier paper the curves in the present paper are designated respectively "electric vector polarized in plane of incidence" and "electric vector polarized perpendicular to plane of incidence."

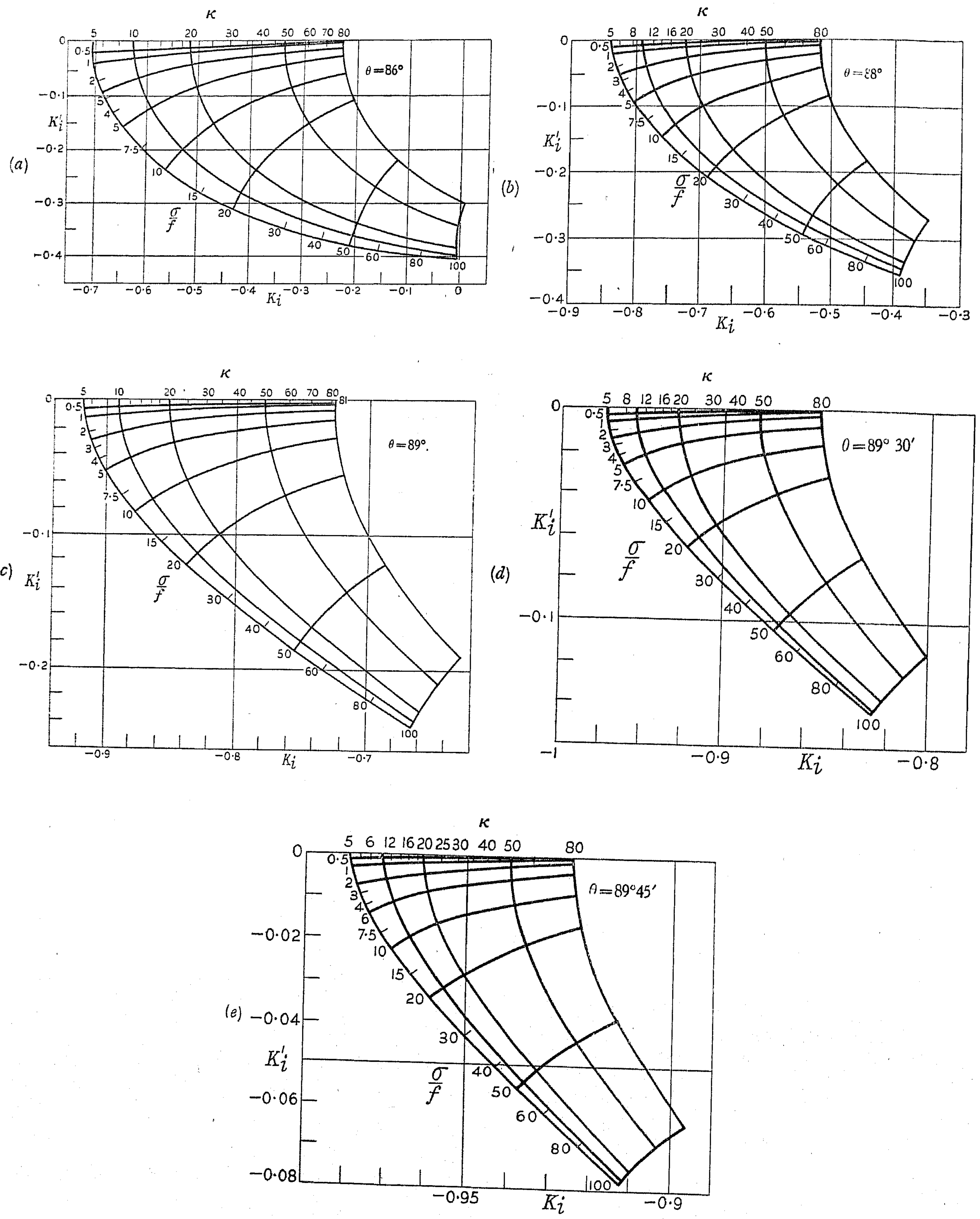

Fig. 2.—Curves giving the in-phase (K_i) and in-quadrature (K_i') components of the reflection coefficient for various angles of incidence (θ), for radiation polarized with the electric field in the plane of incidence.

Table 1

θ	σ/f	$\kappa = 5$		$\kappa = 10$		$\kappa = 20$		$\kappa = 50$		$\kappa = 81$	
		$-K_i$	$-K_i'$	$-K_i$	$-K_i'$	$-K_i$	$-K$	$-K_i$	$-K_i'$	$-K_i$	$-K_i'$
86°	0	0·7032	0·0	0·6228	0·0	0·5151	0·0	0·3349	0·0	0·2257	0·0
	0·5	0·7025	0·01903	0·6219	0·01359	0·5150	0·008698	0·3349	0·004349	0·2257	0·002893
	1	0·7004	0·03811	0·6212	0·02710	0·5145	0·01737	0·3348	0·008695	0·2257	0·005785
	2·5	0·6844	0·09185	0·6132	0·06610	0·5114	0·04305	0·3340	0·02170	0·2253	0·01445
	5	0·6415	0·1584	0·5892	0·1224	0·5010	0·08354	0·3314	0·04310	0·2242	0·02882
	10	0·5573	0·2356	0·5278	0·2010	0·4671	0·1515	0·3215	0·08405	0·2196	0·05699
	20	0·4298	0·3097	0·4166	0·2841	0·3858	0·2398	0·2880	0·1542	0·2028	0·1093
	50	0·2047	0·3823	0·2017	0·3689	0·1940	0·3429	0·1617	0·2751	0·1210	0·2215
	100	0·007786	0·4054	0·007440	0·3982	0·006229	0·3839	−0·001202	0·3428	−0·01379	0·3043
88°	0	0·8395	0·0	0·7916	0·0	0·7240	0·0	0·6009	0·0	0·5197	0·0
	0·5	0·8392	0·01110	0·7914	0·008291	0·7239	0·005634	0·6009	0·003129	0·5197	0·002225
	1	0·8382	0·02225	0·7908	0·01653	0·7236	0·01126	0·6008	0·006257	0·5197	0·004449
	2·5	0·8299	0·05410	0·7865	0·04050	0·7219	0·02793	0·6004	0·01562	0·5194	0·01112
	5	0·8071	0·09539	0·7735	0·07596	0·7160	0·05451	0·5988	0·03108	0·5187	0·02218
	10	0·7608	0·1484	0·7395	0·1288	0·6968	0·10068	0·5928	0·06093	0·5158	0·04398
	20	0·6862	0·2090	0·6744	0·1935	0·6488	0·1665	0·5720	0·1139	0·5048	0·08517
	50	0·5385	0·2937	0·5338	0·2842	0·5236	0·2659	0·4885	0·2186	0·4493	0·1811
	100	0·3874	0·3522	0·3855	0·3462	0·3813	0·3344	0·3664	0·3011	0·3483	0·2702
89°	0	0·9164	0·0	0·8901	0·0	0·8517	0·0	0·7783	0·0	0·7270	0·0
	0·5	0·9162	0·006022	0·8899	0·004614	0·8517	0·003251	0·7783	0·001931	0·7270	0·001437
	1	0·9157	0·01208	0·8896	0·009204	0·8515	0·006495	0·7783	0·003861	0·7270	0·002873
	2·5	0·9116	0·02950	0·8875	0·02259	0·8506	0·01613	0·7780	0·009640	0·7269	0·007180
	5	0·9000	0·05262	0·8808	0·04266	0·8476	0·03158	0·7772	0·01920	0·7265	0·01433
	10	0·8761	0·08379	0·8632	0·07363	0·8376	0·05890	0·7739	0·03776	0·7249	0·02846
	20	0·8367	0·1227	0·8287	0·1143	0·8120	0·09988	0·7626	0·07135	0·7187	0·05544
	50	0·7546	0·1864	0·7506	0·1809	0·7424	0·1704	0·7157	0·1431	0·6870	0·1214
	100	0·6635	0·2430	0·6614	0·2392	0·6569	0·2318	0·6424	0·2109	0·6261	0·1916
89° 30′	0	0·9573	0·0	0·9435	0·0	0·9230	0·0	0·8827	0·0	0·8535	0·0
	0·5	0·9572	0·003141	0·9434	0·002440	0·9230	0·001753	0·8826	0·001082	0·8535	0·0008275
	1	0·9570	0·006304	0·9433	0·004867	0·9229	0·003503	0·8826	0·002164	0·8535	0·001655
	2·5	0·9549	0·01542	0·9422	0·01196	0·9225	0·008705	0·8825	0·005403	0·8534	0·004135
	5	0·9491	0·02767	0·9388	0·02266	0·9209	0·01706	0·8821	0·01076	0·8532	0·008257
	10	0·9370	0·04460	0·9299	0·03946	0·9158	0·03199	0·8804	0·02121	0·8524	0·01641
	20	0·9170	0·06660	0·9124	0·06234	0·9028	0·05495	0·8746	0·04030	0·8492	0·03207
	50	0·8745	0·1055	0·8720	0·1026	0·8668	0·09713	0·8501	0·08281	0·8326	0·07138
	100	0·8259	0·1442	0·8243	0·1421	0·8211	0·1381	0·8110	0·1268	0·7999	0·1163
89° 45′	0	0·9784	0·0	0·9713	0·0	0·9607	0·0	0·9396	0·0	0·9240	0·0
	0·5	0·9784	0·001605	0·9713	0·001255	0·9607	0·0009112	0·9395	0·0005742	0·9240	0·0004458
	1	0·9783	0·003221	0·9712	0·002504	0·9607	0·001821	0·9395	0·001148	0·9240	0·0008915
	2·5	0·9772	0·007890	0·9707	0·006157	0·9605	0·004526	0·9395	0·002868	0·9239	0·002228
	5	0·9743	0·01419	0·9690	0·01168	0·9597	0·008879	0·9393	0·005714	0·9238	0·004449
	10	0·9683	0·02302	0·9645	0·02044	0·9571	0·01669	0·9384	0·01127	0·9234	0·008847
	20	0·9582	0·03472	0·9557	0·03257	0·9506	0·02885	0·9355	0·02148	0·9218	0·01731
	50	0·9367	0·05620	0·9353	0·05473	0·9324	0·05194	0·9230	0·04467	0·9134	0·03886
	100	0·9119	0·07869	0·9110	0·07764	0·9091	0·07557	0·9031	0·06974	0·8967	0·06435

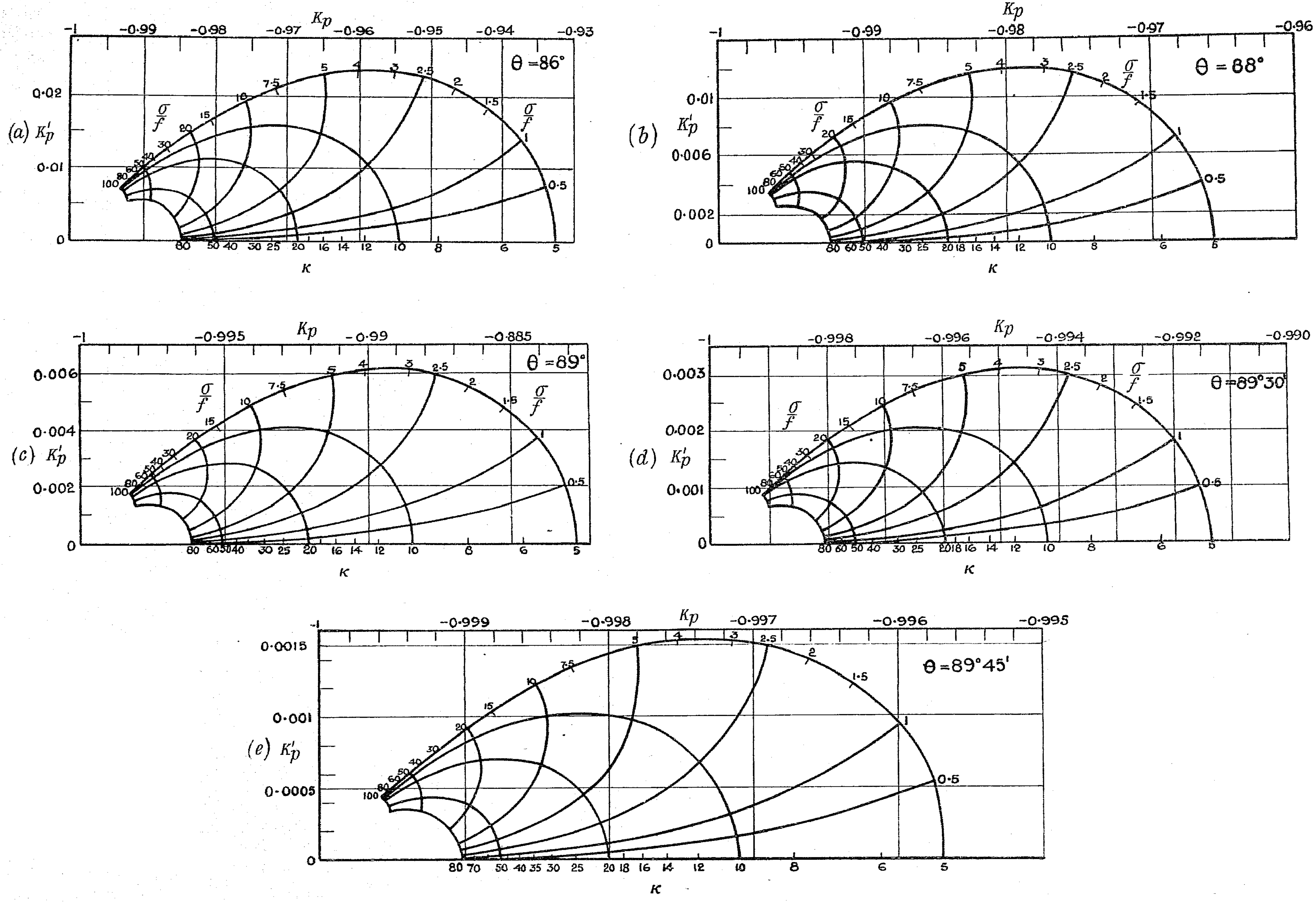

Fig. 3.—Curves giving the in-phase (K_p) and in-quadrature (K_p') components of the reflection coefficient for various angles of incidence (θ), for radiation polarized with the electric field perpendicular to the plane of incidence.

Table 2

θ	σ/f	$\kappa = 5$		$\kappa = 10$		$\kappa = 20$		$\kappa = 50$		$\kappa = 81$	
		$-K_p$	K'_p	$-K_p$	K'_p	$-K_p$	K'_p	$-K_p$	K'_p	$-K_p$	K'_p
86°	0	0·93263	0·0	0·95456	0·0	0·96850	0·0	0·98027	0·0	0·98452	0·0
	0·5	0·93406	0·007837	0·95476	0·002447	0·96853	0·0008143	0·98027	0·0001993	0·98452	0·00009597
	1	0·93771	0·01421	0·95535	0·004789	0·96863	0·001620	0·98028	0·0003983	0·98453	0·0001919
	2·5	0·95125	0·02280	0·95873	0·01045	0·96926	0·003914	0·98034	0·0009904	0·98454	0·0004102
	5	0·96514	0·02300	0·96574	0·01494	0·97117	0·007013	0·98056	0·001944	0·98461	0·0009506
	10	0·97621	0·01912	0·97517	0·01577	0·97583	0·01023	0·98135	0·003624	0·98487	0·001849
	20	0·98371	0·01453	0·98304	0·01338	0·98237	0·01100	0·98359	0·005791	0·98574	0·003341
	50	0·98995	0·009565	0·98973	0·009297	0·98937	0·008725	0·98882	0·006917	0·98894	0·005281
	100	0·992957	0·006856	0·992875	0·006765	0·992723	0·006575	0·992362	0·005955	0·992145	0·005287
88°	0	0·96574	0·0	0·97700	0·0	0·98411	0·0	0·990078	0·0	0·992227	0·0
	0·5	0·96645	0·004059	0·97710	0·001253	0·98413	0·0004140	0·990080	0·0001007	0·992227	0·00004839
	1	0·96836	0·007342	0·97741	0·002452	0·98418	0·0008237	0·990084	0·0002013	0·992228	0·00009675
	2·5	0·97538	0·01165	0·97915	0·005343	0·98450	0·001989	0·990116	0·0005005	0·992238	0·0002414
	5	0·98247	0·01171	0·98274	0·007608	0·98548	0·003561	0·990227	0·0009821	0·992271	0·0004793
	10	0·98807	0·009682	0·98753	0·007992	0·98785	0·005179	0·990628	0·001830	0·992400	0·0009320
	20	0·991844	0·007327	0·991501	0·006752	0·991157	0·005555	0·991763	0·002922	0·992841	0·001684
	50	0·994970	0·004810	0·994861	0·004676	0·994675	0·004388	0·994397	0·003480	0·994453	0·002657
	100	0·996476	0·003442	0·996435	0·003397	0·996358	0·003301	0·996176	0·002991	0·996066	0·002656
89°	0	0·98270	0·0	0·98843	0·0	0·992024	0·0	0·995026	0·0	0·996105	0·0
	0·5	0·98308	0·002065	0·98849	0·0006340	0·992032	0·0002087	0·995027	0·00005062	0·996105	0·00002429
	1	0·98406	0·003732	0·98864	0·001240	0·992057	0·0004152	0·995029	0·0001012	0·996106	0·00004857
	2·5	0·98763	0·005901	0·98952	0·002700	0·992220	0·001003	0·995045	0·0002515	0·996111	0·0001212
	5	0·991214	0·005910	0·991337	0·003838	0·992712	0·001794	0·995101	0·0004936	0·996128	0·0002406
	10	0·994029	0·004871	0·993752	0·004022	0·993908	0·002606	0·995302	0·0009195	0·996192	0·0004679
	20	0·995920	0·003679	0·995747	0·003391	0·995572	0·002790	0·995873	0·001467	0·996414	0·0008449
	50	0·997484	0·002411	0·997429	0·002344	0·997336	0·002200	0·997196	0·001745	0·997223	0·001332
	100	0·998238	0·001724	0·998217	0·001702	0·998178	0·001654	0·998087	0·001499	0·998032	0·001331
89° 30′	0	0·991311	0·0	0·994199	0·0	0·996004	0·0	0·997510	0·0	0·998051	0·0
	0·5	0·991505	0·001041	0·994226	0·0003189	0·996008	0·0001048	0·997510	0·00002537	0·998051	0·00001217
	1	0·991998	0·001881	0·994302	0·0006236	0·996020	0·0002085	0·997511	0·00005070	0·998051	0·00002433
	2·5	0·993798	0·002969	0·994748	0·001357	0·996102	0·0005032	0·997519	0·0001261	0·998053	0·00006071
	5	0·995602	0·002968	0·995661	0·001927	0·996350	0·0009002	0·997547	0·0002474	0·998062	0·0001205
	10	0·997013	0·002443	0·996873	0·002017	0·996950	0·001307	0·997648	0·0004609	0·998094	0·0002344
	20	0·997959	0·001843	0·997872	0·001699	0·997785	0·001398	0·997935	0·0007351	0·998205	0·0004232
	50	0·998742	0·001207	0·998714	0·001174	0·998668	0·001102	0·998597	0·0008739	0·998611	0·0006672
	100	0·9991188	0·0008630	0·9991084	0·0008516	0·9990891	0·0008277	0·9990433	0·0007500	0·9990156	0·0006660
89° 45′	0	0·995646	0·0	0·997095	0·0	0·998000	0·0	0·998754	0·0	0·9990248	0·0
	0·5	0·995744	0·0005229	0·997109	0·0001599	0·998002	0·00005249	0·998754	0·00001270	0·9990249	0·00000609
	1	0·995991	0·0009443	0·997147	0·0003127	0·998008	0·0001044	0·998755	0·00002538	0·9990250	0·00001214
	2·5	0·996895	0·001489	0·997371	0·0006804	0·998050	0·0002521	0·998759	0·00006312	0·9990262	0·00003039
	5	0·997799	0·001487	0·997829	0·0009658	0·998173	0·004509	0·998773	0·0001239	0·9990305	0·00006033
	10	0·998506	0·001223	0·998436	0·001010	0·998474	0·0006544	0·998824	0·0002307	0·9990467	0·0001173
	20	0·998980	0·0009226	0·998936	0·0008505	0·998892	0·0006999	0·998967	0·0003679	0·9991023	0·0002118
	50	0·9993710	0·0006040	0·9993572	0·0005872	0·9993338	0·0005512	0·9992985	0·0004373	0·9993052	0·0003338
	100	0·9995594	0·0004317	0·9995542	0·0004260	0·9995445	0·0004141	0·9995216	0·0003752	0·9995077	0·0003332

and

$$K'_p = \frac{-2d\cos\theta}{\cos^2\theta + (c^2+d^2) + 2c\cos\theta} \quad . \quad . \quad (6)$$

In these equations c and d are given by

$$c = \frac{1}{\sqrt{2}}\sqrt{\left\{\sqrt{\left[(\kappa-\sin^2\theta)^2 + 4\frac{\sigma^2}{f^2}\right]} + (\kappa - \sin^2\theta)\right\}}$$

$$d = -\frac{1}{\sqrt{2}}\sqrt{\left\{\sqrt{\left[(\kappa-\sin^2\theta)^2 + 4\frac{\sigma^2}{f^2}\right]} - (\kappa - \sin^2\theta)\right\}}$$

GRAPHICAL DETERMINATION OF REFLECTION COEFFICIENTS

The method for the determination of reflection coefficients used in both the earlier and the present papers is best illustrated by reference to Fig. 1. In this Figure the abscissae and ordinates represent respectively the two rectangular components K and K' of the reflection coefficient. As can be seen from equations (1) and (2), K and K' for both vertically and horizontally polarized waves are functions of κ, (σ/f), and the angle of incidence θ. This means that if Fig. 1 is assumed to apply for a given angle of incidence then each point in the Figure determines the components K and K' of the reflection coefficient, and therefore corresponds to definite values of the factors κ and σ/f. In order to determine these factors, K and K' are calculated from equations (3) to (6) for a series of values of κ and σ/f, and the two sets of intersecting curves shown in Fig. 1 obtained by drawing smooth curves through the points corresponding, in turn, to equal values of κ and σ/f. The point of intersection of any two curves gives the components K and K' of the reflection coefficient for a medium having the values κ and σ/f common to the two curves intersecting at that point. The reflection coefficient is fully known, since its magnitude is given by the length of the vector from the origin of co-ordinates to the point considered and the phase-change occurring on reflection is given by the angle which that vector makes with the horizontal axis. If a sufficient number of curves are given for a series of values of angle of incidence the reflection coefficient for any medium and any angle of incidence can be determined by interpolation. It will be seen from equations (1) and (2) that the two sets of curves in Fig. 1 are orthogonal (i.e. they intersect at right angles to one another). This simplifies the interpolation.

Figs. 2 (*a*), (*b*), (*c*), (*d*) and (*e*), have been prepared in the manner described above and give the reflection coefficient for vertically polarized waves for angles of incidence of 86°, 88°, 89°, 89° 30′, and 89° 45′ respectively. The range of values of κ and σ/f covers most of those ordinarily found in radio practice. The calculated values of the reflection coefficient corresponding to the points of intersection in Fig. 2 are given in Table 1. From this Table larger-scale diagrams can be prepared than are suitable for publication, and greater accuracy of interpolation thereby obtained. The interpolation may, of course, be made directly from the Table, but the orthogonal nature of the two sets of curves in a prepared diagram is usually a valuable help. Fig. 3 and Table 2 give similar information for horizontally polarized waves.

CALCULATION OF FIELD FROM REFLECTION COEFFICIENT

(a) Ray Theory Applicable

Let T (Fig. 4) represent a radiator of moment m (i.e. the product of effective height and current). The field at a receiver R according to the ray theory is the same as that due to the transmitter T and a second radiator of moment $(K + jK')m$ at the image point T′ of T in the reflecting surface S. K and K' are the rectangular components of the Fresnel reflection coefficient and are given by equations (3) and (4), or (5) and (6), according to the orientation of the radiator at T. If the horizontal distance d between T and R is very much greater than the heights h_T and h_R of T and R above the reflector, the path-difference between the direct and reflected rays arriving at R from T is approximately $2h_Th_R/d$. This corresponds to a small phase-difference of $4\pi h_Th_R/(\lambda d)$ for a wavelength λ. The electric field at a distance d in free space from a radiator of moment m is $60\pi m/(\lambda d)$. If the units of current and length in this expression are amperes and metres respectively the field is given in volts per metre. The resultant field at R due to the radiator m at T and its image $(K + jK')m$ at T′ is given, therefore, by the vector addition of the two fields $60\pi m/(\lambda d)$ and $60\pi(K + jK')m/(\lambda d)$ differing in phase by the angle $4\pi h_Th_R/(\lambda d)$. The magnitude of this field can be expressed in the form

$$\epsilon = \frac{60\pi m}{\lambda d}\left(1 + R_v + \frac{4\pi j h_T h_R}{\lambda d}\right) \quad . \quad . \quad (7)$$

It is to be noted that equation (7) applies only to cases in which the heights of the transmitter and receiver are both small compared with the horizontal distance between them and also, of course, on the assumption that the conditions of propagation are such that the ray theory can be applied. From equation (1), the field ϵ given by equation (7) reduces, for vertically polarized waves, to

$$\epsilon = \frac{60\pi m}{\lambda d} \times \left\{\frac{2[k - 2j(\sigma/f)]\cos\theta}{[\kappa - 2j(\sigma/f)]\cos\theta + \sqrt{[\kappa - 2j(\sigma/f) - \sin^2\theta]}} + j\frac{4\pi h_T h_R}{\lambda d}\right\} \quad . \quad . \quad (8)$$

If h_T and $h_R \ll d$, $\cos\theta \simeq (h_T + h_R)/d$, and $\sin\theta \simeq 1$; so that

$$\epsilon \simeq \frac{60\pi m}{\lambda d^2}\left\{\frac{2[\kappa - 2j(\sigma/f)](h_T + h_R)}{\sqrt{[\kappa - 1 - 2j(\sigma/f)]}} + j\frac{4\pi h_T h_R}{\lambda}\right\} \quad (9)$$

The corresponding expression for the horizontal field from a horizontal aerial of moment m is, from equation (2),

$$\epsilon \simeq \frac{60\pi m}{\lambda d^2}\left\{\frac{2(h_T + h_R)}{\sqrt{[\kappa - 1 - 2j(\sigma/f)]}} + j\frac{4\pi h_T h_R}{\lambda}\right\} \quad (10)$$

With either type of polarization, therefore, the electric field varies inversely as the square of the distance between transmitter and receiver. For large values of trans-

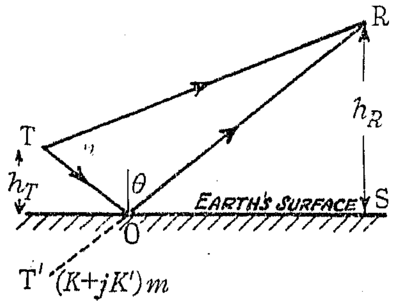

Fig. 4.—Diagram showing direct and reflected paths between elevated transmitter (T) and receiver (R).

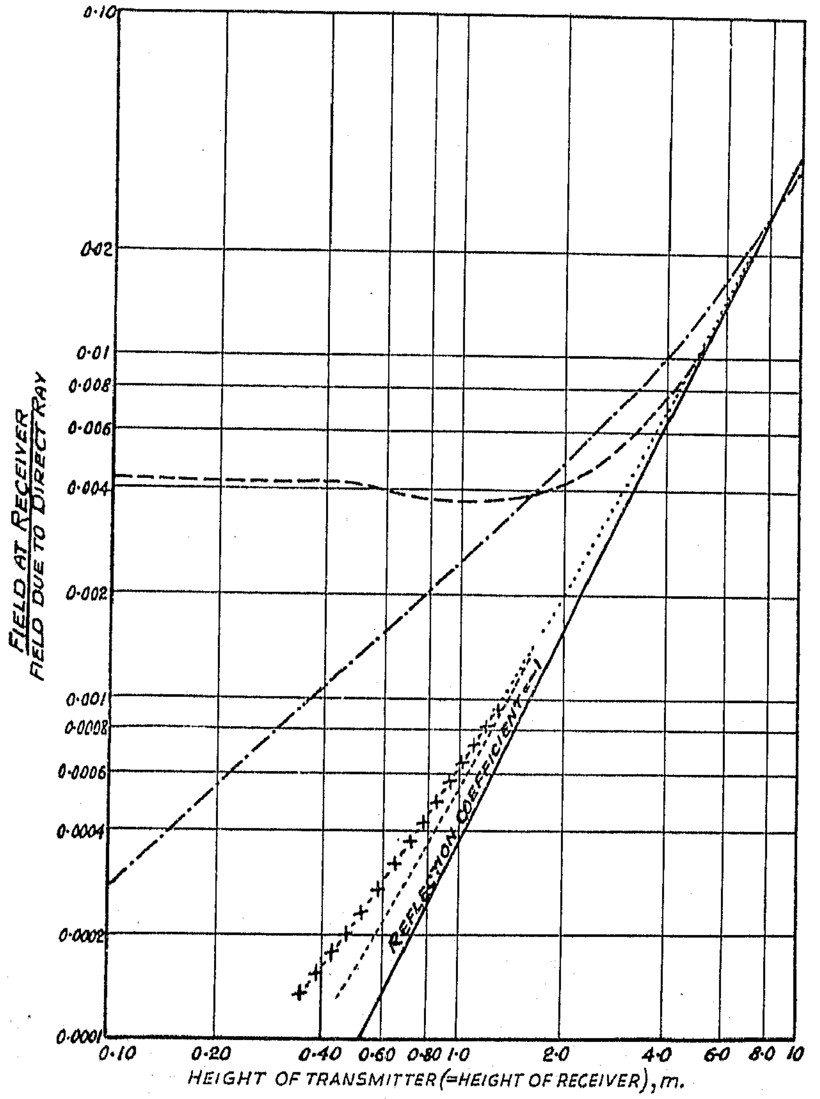

Fig. 5.—Wavelength = 7·5 m., distance from transmitter to receiver = 4 500 m., κ = 5, σ = 10^8 e.s.u.

— · — · Vertical field (ray theory).
----- Horizontal field (ray theory).
— — — Vertical field (complete theory).
× — × — Horizontal field (complete theory).

mitter and receiver heights the second term in the brackets in equations (9) and (10) predominates. As the values of h_T and h_R are reduced, however, the first term in each of these relations becomes relatively more important, until finally for small transmitter and receiver heights it is much larger than the second term. In Fig. 5 the amplitude of electric field calculated from equations (9) and (10) is shown graphically for the conditions specified and for various heights of transmitter and receiver. The full-line curve represents the field given by the second term within the brackets in either equation (9) or equation (10), and gives the field for a medium for which the reflection coefficient is unity and the change in phase on reflection is π. The chain and dotted curves are those given by equations (9) and (10) respectively. It will be noted that the dotted curve for horizontally polarized waves follows the full-line curve much more closely than does the chain curve for vertically polarized waves. The difference in the propagation characteristics of horizontally and vertically polarized waves is due to the smaller ratio of the first to second terms in equation (10) than that of the corresponding terms in equation (9). In Fig. 6 the relative fields at a series of wavelengths for vertically and horizontally polarized waves are given for a constant height of transmitter and receiver and a fixed horizontal distance between them. Here again the difference between the propagation characteristics of radiation having these two polarizations will be observed and also the manner in which as the wavelength is decreased the field approximates to that given for a medium having a reflection coefficient of −1. This latter effect is due, of course, to the increase in magnitude of the second terms in both equation (9) and equation (10) as the wavelength λ is decreased.

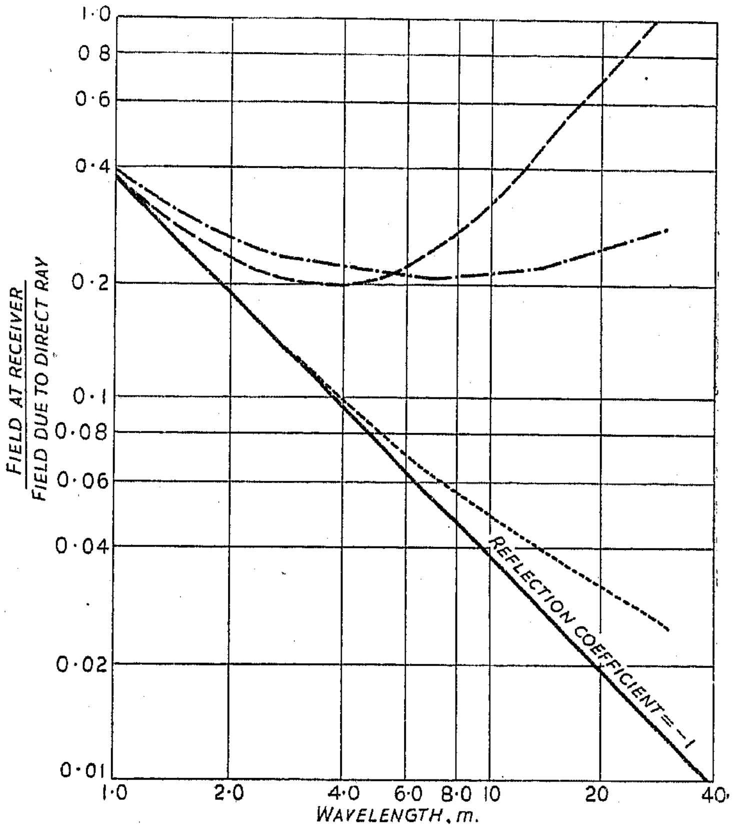

Fig. 6

Height of transmitter = height of receiver = 1·75 m.
Distance from transmitter to receiver = 100 m.
κ = 10, σ = 10^8 e.s.u.
— · — · Vertical field (ray theory).
— — — Vertical field (complete theory).
- - - - - Horizontal field (ray theory and complete theory).

(b) Ray Theory not Applicable

The radiation reflected from the ground is due to the re-radiation by the molecules in the ground which are polarized by the field incident on them from the transmitter. The radiation from any dipole, whether it be a component of an aerial or a polarized molecule, is extremely complex at distances from it less than a wavelength of the current flowing in it. On the simple ray theory the radiation from a transmitting aerial of moment m in the neighbourhood of a reflector is equivalent to that from the original aerial and a second similar aerial of moment $(K + jK')m$ at the image position of the transmitting aerial in the reflecting surface, $(K + jK')$ being the appropriate Fresnel reflection coefficient for radiation incident on that surface at the angle of incidence and with the state of polarization determined by the dispositions of transmitter and receiver with respect to the reflector. A true image, however, can be formed only if all the rays arriving at the receiver after reflection undergo the same change on reflection. Owing to the finite size of both transmitter and receiver these rays cover a small range of angles of incidence. In any particular problem, therefore, a Fresnel image of the transmitting aerial can only be regarded as equivalent approximately to the total radiation reflected to the receiver if the rate of change of reflection coefficient with angle of incidence is small. Actually it is more convenient to determine the rate of change of $(1 + R)$ as given by equations (1) and (2) with the complement of the angle of incidence. From these two relations it can be shown that, for values of the angle of incidence θ equal nearly to $\pi/2$,

$$\frac{\partial(1 + R_h)}{\partial\left(\frac{\pi}{2} - \theta\right)} \Bigg/ \frac{\partial(1 + R_v)}{\partial\left(\frac{\pi}{2} - \theta\right)} = \frac{1}{\kappa - 2j\frac{\sigma}{f}} \quad . \quad . \quad (11)$$

As the minimum value for $\kappa - 2j(\sigma/f)$ lies between 5 and 10 for dry soil[2] the rate of change of reflection coefficient with angle of incidence is much smaller for horizontally than for vertically polarized radiation. The simple ray theory should apply, therefore, more closely for horizontally than for vertically polarized waves. The different rates of change of reflection coefficient for these two states of polarization at large angles of incidence are shown by the two curves in Fig. 7, which apply for a reflector having a dielectric constant equal to 10 and negligible conductivity.

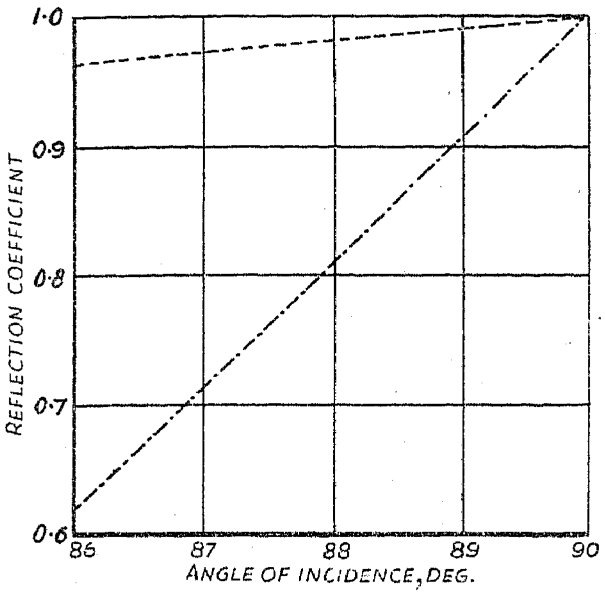

Fig. 7.—Graphs showing reflection coefficient plotted against angle of incidence, for ground constants $\kappa = 10$, and $\sigma = 0$.

— · — · Vertical polarization.
- - - - - Horizontal polarization.

Table 3

	Polarization	
	Vertical	Horizontal
Fresnel reflection coefficient	− 0·7395 − 0·129*j*	− 0·988 + 0·008*j*
Effective reflection coefficient	− 0·202 − 0·94*j*	− 0·984 + 0·006*j*
Advance in phase of effective reflection coefficient over Fresnel reflection coefficient	+ 63°	+ 0·10°

Wavelength = 30 m., $\kappa = 10$, $\sigma = 10^8$ e.s.u.
Distance from transmitter to receiver = 100 m.
Height of transmitter = height of receiver = 1·75 m.

It can be shown from Hertz's equations that, within two cones making angles of approximately 55° with the axis of a dipole, the electric field at a given point measured in the direction parallel to the dipole leads the true radiation field in phase. This advance in phase occurs because within these cones the induction component of the field at any point leads the radiation component in phase by an angle of $\pi/2$, while the static field is in phase with the radiation field. In directions outside the two cones formed in this way the resultant electric field parallel to the dipole lags on the radiation component. The effect of the static and induction fields becomes more pronounced as the distance from the dipole at which the field is measured is reduced.

When vertically polarized waves are incident on the ground at grazing incidence, dipoles are formed within the ground for which a component of moment is in the vertical direction. If a vertical receiving aerial is placed near the ground, so that the static and induction fields of the dipoles in the ground are large in its vicinity, there is an advance in phase of the resultant re-radiation from the reflector calculated from only the radiation components of these dipoles. This is because that part of the ground nearest the aerial and for which the induction and static fields of the ground dipoles are most pronounced lies within one of the cones coaxial with the receiving aerial, within which the resultant vertical field from each vertical dipole leads the radiation field at the receiving aerial. In the case of a horizontal receiving aerial the advance in phase of the resultant horizontal electric field over the radiation component alone is much less pronounced than for the vertical receiving aerial at the same distance from a reflector. This result is obtained because the part of the reflector nearest to the horizontal aerial is in such a position with respect to it that the field from it lags on the radiation component. The total effect, however, as can be shown roughly by graphical integration, is still an advance in phase but is much smaller in magnitude than for the vertical receiving aerial at the same distance from the reflector.

The Fresnel reflection coefficients are derived on the assumption of plane-wave propagation, which implies that both transmitter and receiver are at more than a certain minimum distance from the reflecting surface. Under such conditions only the radiation component of the fields from the radiating dipoles is appreciable. Reducing the height of either transmitter or receiver so as to accentuate the static and induction fields of the dipoles should produce, on this hypothesis, an apparent advance in phase of the effective reflection coefficient compared with that deduced for the same disposition of transmitter and receiver from the Fresnel equations. The results obtained in a particular case for both vertically and horizontally polarized waves are given in Table 3.

The relatively great difference between the effective and Fresnel reflection coefficients for vertically polarized waves compared with that for horizontally polarized waves is evident from the figures given in Table 3. The analytical study of this problem has been undertaken recently by Wise[3] and Norton,[4] but they do not emphasize the physical significance of the problem or the difference between the propagation characteristics of vertically and horizontally polarized waves.

Norton has given formulae for all the components of the electromagnetic field produced by vertical and horizontal dipoles and aerials of finite length at any height above a plane imperfectly conducting earth. These formulae are based on expressions obtained by Van der Pol[5] and Wise from the original equations of Sommerfeld.[6]

In the present paper only those formulae will be considered which apply to rectilinear antennae carrying relatively high-frequency radio currents and placed at moderate to small heights above the ground. It is important to note that, in addition to the form of the equations derived below being slightly different from that of those given by Norton, the sense of rotation of the vector representing the electric field due to phase retardation by time or distance is in the clockwise direction. Norton's formula for the vertical electric field from a vertical dipole of moment m may be written, for large angles of incidence,

$$\epsilon = \frac{60\pi m}{\lambda}\left\{\frac{e^{\frac{-2\pi jR_1}{\lambda}}}{R_1} + R_v\frac{e^{\frac{-2\pi jR_2}{\lambda}}}{R_2} + (1-R_v)\left[1 - \frac{\kappa - 2j\frac{\sigma}{f} - \sin^2\theta}{\left(\kappa - 2j\frac{\sigma}{f}\right)^2}\right]F\,\frac{e^{\frac{-2\pi jR_2}{\lambda}}}{R_2} + 2\left[\frac{\kappa - 2j\frac{\sigma}{f} - \sin^2\theta}{\left(\kappa - 2j\frac{\sigma}{f}\right)^2}\right]\cos\theta\,\frac{e^{\frac{-2\pi jR_2}{\lambda}}}{R_2} + \left[\frac{\lambda}{2\pi jR_1} + \left(\frac{\lambda}{2\pi jR_1}\right)^2\right]\frac{e^{\frac{-2\pi jR_1}{\lambda}}}{R_1} + \left[\frac{\lambda}{2\pi jR_2} + \left(\frac{\lambda}{2\pi jR_2}\right)^2\right]\frac{e^{\frac{-2\pi jR_2}{\lambda}}}{R_2}\right\} \quad . \; . \; . \quad (12)$$

in which

θ = angle of incidence,
R_1 = length of direct path TR (Fig. 4),
R_2 = length of indirect path TOR = T′OR (Fig. 4),
λ = wavelength of radiation,

and
$$F = 1 + 2j\sqrt{w}e^{-w}\int_{-j\sqrt{w}}^{\infty} e^{-x^2}dx$$

w being given by

$$w = \frac{-4\pi j(h_T + h_R)^2}{\lambda d(1+R_v)^2}$$

which can be written

$$w = \frac{-\pi j\left(\kappa - 2j\frac{\sigma}{f} - 1\right)d}{\lambda\left(\kappa - 2j\frac{\sigma}{f}\right)^2} \quad . \; . \; . \quad (13)$$

when the horizontal distance d between the transmitter and receiver is large compared with the heights h_T and h_R of the transmitter and receiver. Equation (12) is rather complicated, but most of the terms in it are of small magnitude in practice. The expression for F can be evaluated* by either of the two series

$$F = -\frac{1}{2w} - \frac{1.3}{(2w)^2} - \frac{1.3.5}{(2w)^3} - \ldots \text{ for } |w| > 10 \quad . \quad (14)$$

$$= 1 + j\sqrt{(\pi w)}e^{-w} - \left[2w - \frac{(2w)^2}{1.3} + \frac{(2w)^3}{1.3.5} - \ldots\right] \quad \text{for } |w| \text{ small} \quad . \; . \quad (15)$$

By using one or other of these two series it is usually found that only a few terms are required.

Except for distances small compared with the wavelength, equation (12) can be written in the approximate form

$$\epsilon = \frac{60\pi m}{\lambda}\left\{\frac{e^{\frac{-2\pi jR_1}{\lambda}}}{R_1} + \left[R_v + (1-R_v)F\right]\frac{e^{\frac{-2\pi jR_2}{\lambda}}}{R_2}\right\} \quad . \quad (16)$$

If the horizontal distance d between transmitter and receiver is large, $F \simeq -1/(2w)$ and $R_1 \simeq R_2$, so that equation (16) becomes

$$\epsilon = \frac{60\pi m}{\lambda d}\left\{1 + \left[R_v - \frac{(1-R_v)}{2w}\right]e^{\frac{-4\pi jh_T h_R}{\lambda d}}\right\}$$

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* E. T. Whittaker and G. Robinson: "Calculus of Observations," p. 180.

$$= \frac{60\pi m}{\lambda d}\left\{1+\left[R_v+\frac{1-R_v}{2\pi jd}\frac{\lambda\left(\kappa-2j\frac{\sigma}{f}\right)^2}{\left(\kappa-2j\frac{\sigma}{f}-1\right)}\right]e^{\frac{-4\pi jh_Th_R}{\lambda d}}\right\} \quad (17)$$

$$= \frac{60\pi m}{\lambda d}\left\{1+\left[R_v+\frac{(1-R_v)(1+R_v)^2\lambda d}{8\pi j(h_T+h_R)^2}\right]e^{\frac{-4\pi jh_Th_R}{\lambda d}}\right\} \quad . \quad . \quad (18)$$

Whether equation (17) or equation (18) is used is largely a matter of personal preference, but certain characteristics of vertically polarized waves can be derived more readily from equation (17). When the reflected wave is incident on the earth at an angle very nearly equal to $\pi/2$, $(1-R_v)$ approximates to 2 and equation (17) reduces to

$$\epsilon = \frac{60\pi m}{\lambda d}\left\{1+R_ve^{\frac{-4\pi jh_Th_R}{\lambda d}}+\frac{\lambda\left(\kappa-2j\frac{\sigma}{f}\right)^2}{\pi jd\left(\kappa-2j\frac{\sigma}{f}-1\right)}e^{\frac{-4\pi jh_Th_R}{\lambda d}}\right\} \quad (19)$$

Equation (19) is extremely useful, as the field given by

$$\epsilon = \frac{60\pi m}{\lambda d}\left\{1+R_ve^{\frac{-4\pi jh_Th_R}{\lambda d}}\right\}$$

and represented by the first two terms within the brackets in equation (19) is exactly that determined from the simple ray theory, while the remaining term within the same brackets for a given distance d is of constant magnitude and its phase changes only slowly with the heights of transmitter and receiver. The resultant electric field near the earth at a constant distance from a vertical dipole can therefore be regarded as the vector addition of two fields, one that would be obtained on the assumption of the simple ray theory and the second a constant field independent in magnitude of the height of either transmitter or receiver. This feature is illustrated in Fig. 5, in which for the conditions specified the chain line shows the field calculated from the ray theory and the horizontal portion of the broken line that for the constant term in equation (19), which, incidentally, corresponds to the Sommerfeld surface wave. It will be seen that as the heights of the transmitter and receiver are increased the complete field [shown by the broken line and calculated actually from the full expression in equation (12)] passes from being equal to the field due to the Sommerfeld surface wave for zero and low heights and finally becomes equal to that given by the ray theory. Equation (19) has been derived from equation (17), which is valid only if $|w|$ in equation (13) is greater than 10. As the last term within the brackets in equation (19) is equal to $-1/w$ this condition means that equation (19) can only be assumed to give the correct result for the electric field if the absolute value of the last term within the brackets in equation (19) is less than about 0·1.

The expression given by Norton for the horizontal field from a horizontal dipole at a point in the direction normal to the dipole can be put in the form

$$\epsilon = \frac{60\pi m}{\lambda}\left\{\frac{e^{\frac{-2\pi jR_1}{\lambda}}}{R_1}+\left[R_h+(1-R_h)G\right]\frac{e^{\frac{-2\pi jR_2}{\lambda}}}{R_2} + \text{higher terms in } R_1^2 \text{ and } R_2^2\right\} \quad . \quad (20)$$

in which $G = 1 - 2j\sqrt{v}\int_{-j\sqrt{v}}^{\infty} e^{-x^2}dx$

and $$v = \frac{-4\pi j(h_T+h_R)^2}{(1+R_h)^2\lambda d}$$

which is equal to

$$\frac{-\pi jd\left(\kappa-2j\frac{\sigma}{f}-1\right)}{\lambda}$$

when the distance d is large. Since $|v|$ is always greater than 10 for distances greater than about one wavelength the series given in equation (14) can be used for the evaluation of G, F and w being replaced respectively by G and v. In most practical problems the first term in the series is sufficient, in which case

$$G = \frac{-1}{2v} = \frac{\lambda}{2\pi jd\left(\kappa-2j\frac{\sigma}{f}-1\right)}$$

Equation (20) then reduces to

$$\epsilon = \frac{60\pi m}{\lambda d}\left\{1+\left[R_h+\frac{(1-R_h)\lambda}{2\pi jd\left(\kappa-2j\frac{\sigma}{f}-1\right)}\right]e^{\frac{-4\pi jh_Th_R}{\lambda d}}\right\} \quad . \quad . \quad (21)$$

$$= \frac{60\pi m}{\lambda d}\left\{1+\left[R_h+\frac{(1-R_h)(1+R_h)^2\lambda d}{8\pi j(h_T+h_R)^2}\right]e^{\frac{-4\pi jh_Th_R}{\lambda d}}\right\} \quad . \quad . \quad (22)$$

It will be noted that, except for R_h appearing in place of R_v, equation (22) is identical with equation (18). When the reflected wave is incident at angles very nearly equal to $\pi/2$, equation (21) may be written

$$\epsilon = \frac{60\pi m}{\lambda d}\left\{1+R_he^{\frac{-4\pi jh_Th_R}{\lambda d}}+\frac{\lambda}{\pi jd\left(\kappa-2j\frac{\sigma}{f}-1\right)}e^{\frac{-4\pi jh_Th_R}{\lambda d}}\right\} \quad . \quad . \quad (23)$$

The first two terms within the bracket represent, as in the case of vertically polarized waves, the horizontal electric field calculated on the basis of the ray theory, and the last term a horizontal field of the surface-wave type. The ratio of the magnitudes of the surface-wave fields in equations (19) and (23) is $\left(\kappa-2j\frac{\sigma}{f}\right)^2$. This feature is shown in Fig. 5, from which it is seen that the ratio of the vertical to horizontal fields from equal dipoles in the vertical and horizontal planes respectively increases asymptotically to the limiting value represented by $\left|\left(\kappa - 2j\frac{\sigma}{f}\right)^2\right|$ as the heights of transmitter and receiver are reduced. It will also be noted that the curve giving the vertical electric field is much more nearly constant for small heights than the curve for the horizontal field. This characteristic difference between the characteristics of vertically and horizontally polarized waves is the result of the greater ratio of surface-wave to image fields in the case of vertically polarized than in that of horizontally polarized waves.

In Fig. 6 the relative fields at a series of wavelengths from a given dipole are shown for the two conditions when the dipole is vertical and horizontal and with the receiver at a fixed distance from the transmitter. At short wavelengths the electric fields calculated from the complete expressions given immediately above or from the ray theory (in the previous Section of the paper) agree fairly well, but the departure becomes pronounced in the case of vertically polarized waves when the wavelength is increased. For even the maximum wavelength of 30 m. used in the computation, however, with horizontal polarization, the fields calculated from the equations given by Norton are in such close agreement with those given by the simple ray theory that they cannot be shown as different in the Figure. It will also be noted that the field for horizontally polarized waves is never greatly different from that corresponding to a medium having a reflection coefficient of -1. This latter characteristic of horizontally polarized waves has been used recently in the development of a method for the calibration of short-wave field-strength measuring sets.[7]

CONCLUSIONS

It is pointed out in the paper that the simple ray theory on which the reflection from a surface is assumed to be equivalent to the radiation from an image of the transmitting aerial in the reflecting surface, is not valid for heights of transmitter or receiver which are very small compared with the wavelength. From an analysis given by Norton it is deduced that even in cases for which the image theory cannot be applied the field at the receiver is the vector addition of two fields—one equal to that given by the ray theory and the other a field independent of the height of transmitter or receiver but inversely proportional to the square of the distance between transmitter and receiver. This latter field corresponds to the surface wave which was first determined by Sommerfeld for vertically polarized waves. It is shown in the paper that the surface wave is of much greater importance in the case of vertically polarized waves. As the surface-wave field is independent of height this results in the well-known experimental fact that the vertical field from a low transmitting aerial increases in magnitude with height at a much smaller rate than the horizontal field.

ACKNOWLEDGMENTS

The work described in this paper was carried out as part of the programme of the Radio Research Board, and is published by permission of the Department of Scientific and Industrial Research. The authors are indebted to Dr. R. L. Smith-Rose for suggesting this investigation and for advice on the method of presentation of the paper.

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[The discussion on this paper will be found on page 159.]

AN EXPERIMENTAL INVESTIGATION OF THE PROPAGATION OF RADIATION HAVING WAVELENGTHS OF 2 AND 3 METRES*

By J. S. McPETRIE, Ph.D., D.Sc., Associate Member, and J. A. SAXTON, B.Sc.

(*Paper received* 19*th June*, 1939, *and read before the* WIRELESS SECTION 3*rd April*, 1940.)

SUMMARY

The paper describes the results of an experimental investigation of the characteristics within optical range of the propagation over land of radiation having wavelengths of 2 and 3 metres. It is shown both theoretically and experimentally that for such conditions the propagation of horizontally and vertically polarized waves is identical over a range of transmitter and receiver heights which are small compared with the distance between transmitter and receiver but not small compared with the wavelength. In these circumstances, for a receiver at height h_R metres the field strength in volts per metre at a distance d metres from a half-wavelength radiator at a height h_T metres is given by

$$\epsilon = \frac{90\sqrt{Ph_Th_R}}{\lambda d^2}$$

in which P is the power (watts) radiated at a wavelength λ (metres). Continuous observations of field strength showed that within optical range of the transmitter the fading was less than ± 3 db.

INTRODUCTION

Part of the programme of the Radio Research Board is concerned with the propagation characteristics of ultra-short radio waves, particularly in the wave-band 1–3 m. With the object of investigating these characteristics an experimental and analytical study of the subject has been undertaken recently by the Radio Department, National Physical Laboratory. The present report gives a brief summary of the progress made to date.

THEORY OF PROPAGATION OF SHORT RADIO WAVES

The propagation of long and medium radio waves along the earth's surface is complicated because the transmitter and receiver heights are, in general, small compared with the wavelength. As the wavelength is reduced, however, the surface proximity effect decreases until the electric field at a receiver becomes equal to that determined from the theory of optical reflection at the earth's surface.[1, 2] For wavelengths less than about 20 metres the field given by the optical theory is approximately correct for cases in which the transmitter and receiver heights are each greater than about a wavelength and the distance between transmitter and receiver is not so great that the effects of diffraction become important. The experimental results given in this report show that the optical theory may be used up to a distance equal almost to that represented by the optical range of transmitter and receiver. This result is in agreement with the diffraction theories put forward recently by Van der Pol and Eckersley, and summarized in the form of a series of curves in a recent report.[3]

For a distance between transmitter and receiver which is large compared with the transmitter and receiver heights the ray reflected to the receiver by the ground is incident on that surface at almost grazing incidence. Relatively simple expressions for the electric field from vertical and horizontal aerials respectively have been derived from an analysis first given by Norton.[1] The vertical electric field from a vertical aerial is given by

$$\epsilon = \frac{60\pi m}{\lambda d^2} \times \left[\frac{2(h_T + h_R)\left(\kappa - 2j\frac{\sigma}{f}\right)}{\sqrt{\left(\kappa - 1 - 2j\frac{\sigma}{f}\right)}} + \frac{4\pi j h_T h_R}{\lambda} + \frac{\lambda\left(\kappa - 2j\frac{\sigma}{f}\right)^2}{\pi j\left(\kappa - 1 - 2j\frac{\sigma}{f}\right)}\right] \quad . \quad . \quad . \quad (1)$$

and the corresponding horizontal field from a horizontal aerial by

$$\epsilon = \frac{60\pi m}{\lambda d^2} \times \left[\frac{2(h_T + h_R)}{\sqrt{\left(\kappa - 1 - 2j\frac{\sigma}{f}\right)}} + \frac{4\pi j h_T h_R}{\lambda} + \frac{\lambda}{\pi j\left(\kappa - 1 - 2j\frac{\sigma}{f}\right)}\right] \quad . \quad . \quad . \quad (2)$$

In relations (1) and (2), m represents the moment (product of effective height and current) of the transmitting aerial, h_T and h_R the transmitter and receiver heights, λ the wavelength, d the distance between transmitter and receiver, κ and σ the dielectric constant and conductivity respectively of the ground for radiation of frequency f, and $j = +\sqrt{(-1)}$. Relation (2) gives the horizontal electric field perpendicular to the direction of propagation to which it is assumed that the transmitting aerial is also perpendicular.

The first two terms in relations (1) and (2) give the field obtained on the assumption of plane-wave propagation and therefore optical reflection at the ground, while the last terms give the field due to the so-called surface wave. For ordinary soil in England the values of κ and σ/f at a wavelength of 3 m. are approximately 10 and 1 respectively, so that to a first approximation the effect of ground conductivity can be neglected. If κ is made equal to 10 and σ/f neglected, relations (1) and (2) reduce respectively to:—

* Official communication from the National Physical Laboratory.

$$\epsilon = \frac{60\pi m}{\lambda d^2}\left[\frac{20(h_T + h_R)}{3} + \frac{4\pi j h_T h_R}{\lambda} + \frac{\lambda}{9}\frac{100}{\pi j}\right] \quad (3)$$

and

$$\epsilon = \frac{60\pi m}{\lambda d^2}\left[\frac{2(h_T + h_R)}{3} + \frac{4\pi j h_T h_R}{\lambda} + \frac{\lambda}{9\pi j}\right] . \quad (4)$$

It will be seen that as the wavelength λ is decreased the surface-wave terms in both relations (3) and (4) become smaller, and finally, if the heights of transmitter and receiver are sufficiently great compared with the wavelength, the second term in each expression becomes predominant. For this condition both relations reduce to

$$|\epsilon| = \frac{60\pi m}{\lambda d^2}\cdot\frac{4\pi h_T h_R}{\lambda} \quad . \quad . \quad . \quad . \quad (5)$$

which means that horizontally and vertically polarized waves are propagated equally for grazing incidence provided the transmitter and receiver heights are such that the second term in both relations (3) and (4) is the largest in these relations.

If the units of length and current in relations (1) to (5) are metres and amperes respectively, the field is given in volts per metre. On short waves the radiator consists usually of a system of half-wavelength linear aerials. For a single half-wavelength radiator having a radiation resistance of about 75 ohms, an effective height of λ/π, and carrying a current of I amperes at its centre, the moment m is given by

$$m = \frac{\lambda}{\pi}I$$
$$= \frac{\lambda}{\pi}\sqrt{\left(\frac{P}{75}\right)}$$

in which P is the radiated power in watts. Relation (5) then reduces to

$$\epsilon \simeq 90\sqrt{P}\frac{h_T h_R}{\lambda d^2} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The above brief analysis of the propagation of waves along the earth's surface assumes that that surface is flat, whereas in actual fact it has a radius of curvature of about 6 400 km. The effect of this curvature is to reduce the transmitter and receiver heights to be used in relation (6). It can be shown that, for transmitter and receiver heights h_T and h_R and a distance d between transmitter and receiver, the values for h_T and h_R used in relation (6) should be respectively

$$h_T\left(1 - \frac{h_T d^2}{2R(h_T + h_R)^2}\right) \quad . \quad . \quad . \quad . \quad (7)$$

and

$$h_R\left(1 - \frac{h_R d^2}{2R(h_T + h_R)^2}\right) \quad . \quad . \quad . \quad . \quad (8)$$

It is shown later in the paper that the reduction in electric field introduced in this way is much greater than that found experimentally, and relation (6) with the uncorrected transmitter and receiver heights is found to give the received field under a variety of conditions sufficiently closely for most practical purposes within the optical range.

Relation (6) can also be derived for the same conditions from the simple hypothesis of the incidence of two rays at the receiver, one direct from the transmitter, and the other after reflection from the ground. The reflection coefficient of the ground for grazing incidence is unity and the phase-change on reflection π. The resultant electric field at the receiver is then only a small fraction of the direct ray, namely $7\sqrt{P}/d$. In certain circumstances, such as on the side of a hill, however, there can be more than one ray reflected from the ground and still incident on the receiver. Fig. 1(*a*) gives an example, met with quite often in practice, in which there are two reflected rays. In this case one reflected ray almost neutralizes the direct ray, leaving the resultant field at the receiver equal to that due to the second reflected ray, which, owing to the reflection coefficient being unity, is almost equal to the direct ray. Sometimes there may be even more than two reflected rays, such as in Fig. 1(*b*), in which there are two rays reflected once at the ground and one ray reflected twice. The field in this latter ray undergoes a total phase-change of 2π after the two reflections, so that the field at the receiver due to it is almost equal to, and in phase with, the direct ray. Similarly the two singly-reflected rays are equivalent to one reflected ray of twice the intensity, so that the resultant field is twice that due to the direct ray and one singly-reflected ray. Further examples could be given, but the above are sufficient for the present report.

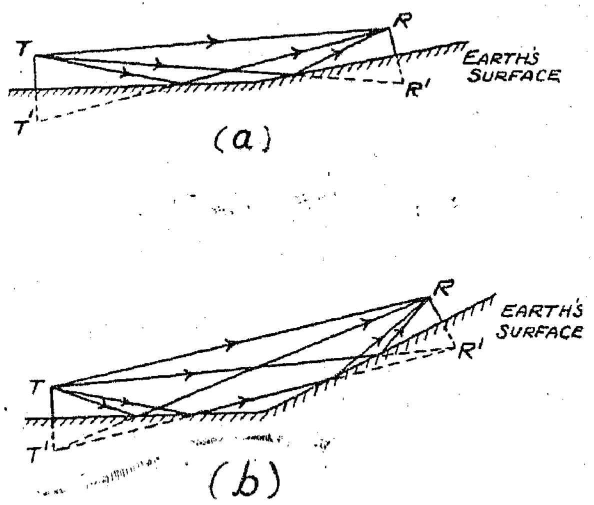

Fig. 1.—Diagrams showing disposition of transmitter and receiver for (*a*) direct plus two singly-reflected rays giving a large field at the receiver; (*b*) direct plus two singly-reflected rays plus one doubly-reflected ray giving a small field at the receiver.

TRANSMITTERS AND AERIAL SYSTEM

Two transmitting stations have been erected, one at the National Physical Laboratory, Teddington, and the other by permission of the British Broadcasting Corporation at Brookmans Park. The transmitter and aerial system installed at Teddington have been described in detail elsewhere.[4] With this transmitter an output of approximately 200 watts can be obtained on any wavelength between 2 m. and 3 m. (100 to 150 Mc./s.). The Brookmans Park transmitter has been loaned by the Post Office; it is crystal-controlled, and gives a radiated output of some 60 watts on a wavelength of either 2·08 or 3·12 m. The aerials at Teddington and Brookmans Park can be rotated into either the vertical or the horizontal direction, so that vertically and horizontally polarized radiation can be studied in rapid succession. The two aerials are situated almost on the edge of two totally different types of country. The Teddington aerial is located at the top of a wooden mast at a height of about 60 ft. above the wide alluvial plain of the Thames Valley lying between Staines and Kew in the N.E.–S.W. direction and Hampton Court and West Drayton in the N.W.–S.E. direction. This region is mostly level, and except for trees and houses is free from major obstructions. The aerial at Brookmans Park is placed at the top of a 30-ft. wooden pole which is fixed to the top of one of the 200-ft. steel masts supporting the aerial for the London National broadcasting transmitter. As Brookmans Park itself is at a height of 420 ft. above mean sea-level the aerial at this site is so placed as to have an optical range across pastoral tree-clad terrain to the Chiltern Hundreds in the north and west, and across densely populated London to the North Downs in the south. By using both transmitters, therefore, it should be possible to investigate the propagation of ultra-short waves over various distinctly different types of terrain. Up to the present only preliminary surveys have been made, and the present report is limited to a brief discussion of the results obtained so far.

The current in the transmitting aerials is determined by measuring the current in a small dipole placed near the aerial. The coefficient of coupling between a half-wavelength aerial and a small dipole for different spacings between the aerial and dipole can be found directly from a curve given elsewhere.[4] Assuming the coupling between the small dipole and the main aerial is known, the current in the main aerial can be computed if the current induced in the small dipole is known. The current in this dipole is determined by means of a vacuo-thermojunction unit placed at its centre, the direct current in the couple being found from the reading of a microammeter near the transmitter, connected to the couple by a pair of twisted insulated wires. By this method the aerial current can be determined in the transmitter hut without the insertion of an instrument in the transmitting aerial and also without the necessity for instrument leads being situated very close to the aerial. The distance between the main and small aerials is about half a wavelength. It has been found that with this spacing the field at the receiver is not affected by the presence of the leads from the couple to the microammeter.

RECEIVERS, AND METHOD OF CALIBRATION

The receivers used in the tests are similar to those described by Colebrook and Gordon-Smith[5] as being suitable for field-strength measurements on ultra-short waves. They are of the superheterodyne type in which the gain of the intermediate-frequency amplifier is adjusted to a constant for zero attenuation by variation of the grid bias applied to the amplifying valves so that the rectified output due to first-circuit noise remains the same. The rectifier in the frequency-change unit is a diode, and the beating oscillator voltage applied to it is sufficiently high for the rectification efficiency to be independent of that voltage. In order to prevent any pulling effect between the oscillator and rectifier circuits the oscillator is tuned to a frequency approximately half that of the received radiation and its second harmonic used to heterodyne the received signal. The half-wavelength aerial is coupled to the receiver by means of a twisted pair of insulated wires, a capacitance screen being placed between the aerial coupling coil and the frequency-change circuit in order to prevent any asymmetry in the receiver affecting the symmetry of the aerial and line circuits. The final balancing of the two wires of the twisted pair is made by the adjustment of two small condensers between each wire and earth at the receiver end of the line so that when the aerial is detached the received signal is a minimum. The ratio between the voltages applied to the receiver with the aerial and feeder system and with the latter alone is of the order of 55 db. The length of the twisted pair is about 3 m. and the measured attenuation in this length of wire about 2·5 db. at a wavelength of 2 m. This attenuation is more than compensated for by the simplicity of the system and its low pick-up factor.

The receiver is calibrated with horizontally polarized waves by the radiation method developed at the National Physical Laboratory.[6] Certain detail modifications were made to suit the higher frequencies involved in the present problem. The receiving aerial is set up horizontally at any convenient height h_R between 1 m. and 3 m. at a distance d of, say, 50 m. from a half-wavelength horizontal radiator. If the transmitting and receiving aerials are both perpendicular to the line between them, the horizontal field at the receiving aerial is given by

$$\epsilon = \frac{240\pi I h_T h_R}{\lambda d^2} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

in which I is the current at the centre of the transmitting aerial at a height h_T above the ground and λ the wavelength at which the calibration is made. If the units of length and current in relation (7) are metres and amperes respectively, the field is given in volts per metre. In order to reduce the effect on the radiation of the transmitting aerial caused by the presence of any box containing the transmitting elements, the aerial was coupled to the transmitter (which was placed on the ground) by a length of about 6 m. of a twisted pair of insulated wires. The radiation from these wires was reduced to a minimum by the adjustment of two small condensers between each wire and the metal box containing the transmitting circuit. The current in the transmitting aerial was measured by two non-contact thermojunctions inserted near the centre of the aerial. The thermojunctions were placed on each side of the centre of the aerial in order to verify in every calibration that the current in each half of the aerial was the same. It was found that when this adjustment was made by means of the two earthing condensers already referred to, the radiation from the leads connecting the aerial and transmitter was a minimum. In this condition the field from the leads alone was about 35 db. below that obtained with the aerial and leads. The calibrations made in this way showed that the receivers could be used to measure field strength down to about 20 μV per metre.

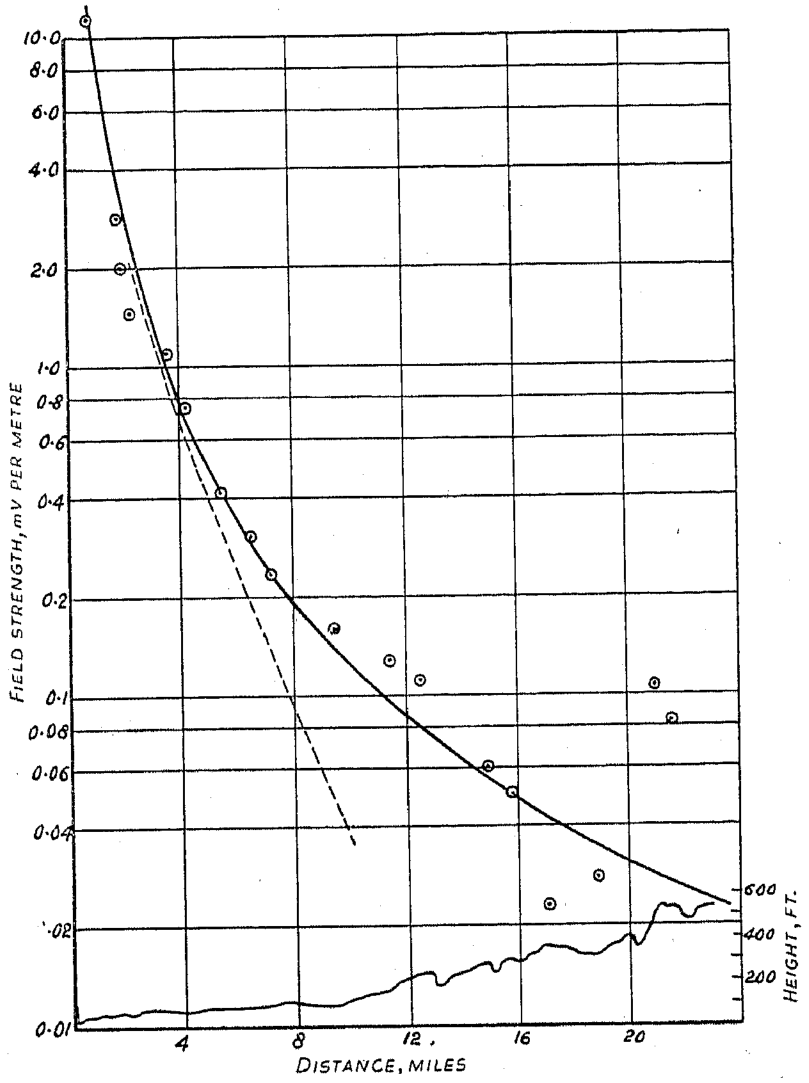

Fig. 2.—Graph showing field strength in N.W. direction plotted against distance.

Teddington transmitter, λ = 3 m., vertical polarization.

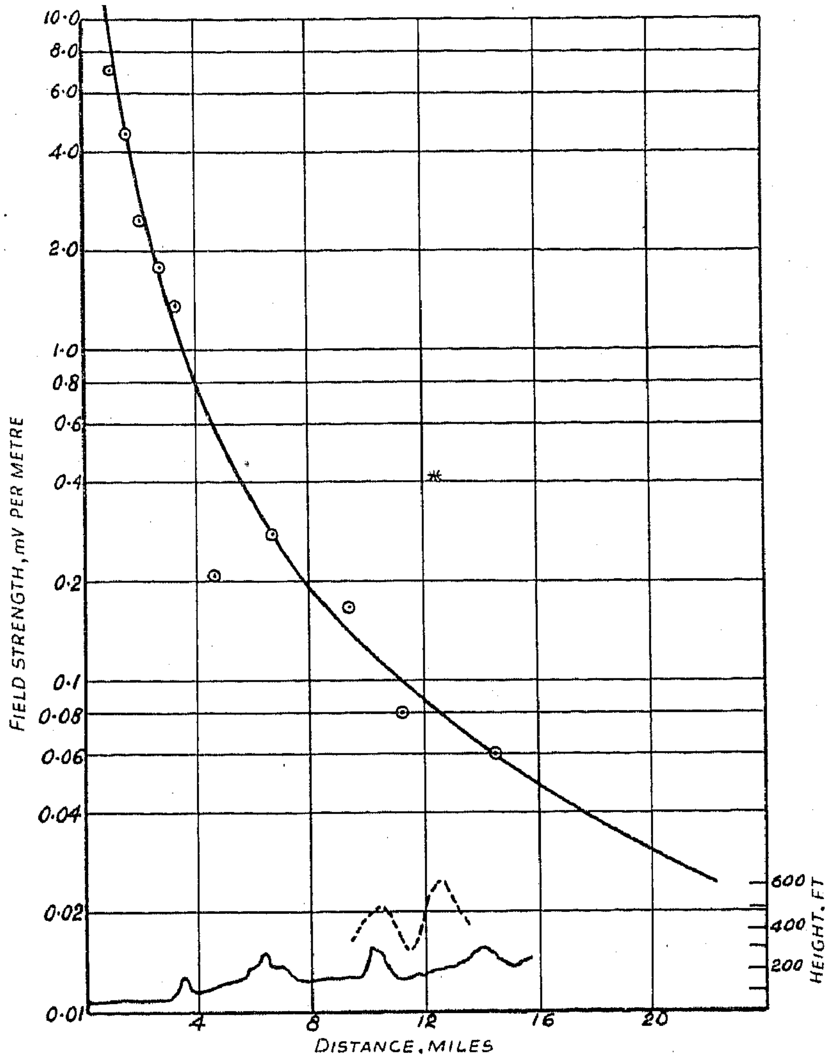

Fig. 4.—Graph showing field strength in S. direction plotted against distance.

Teddington transmitter, λ = 3 m., vertical polarization.

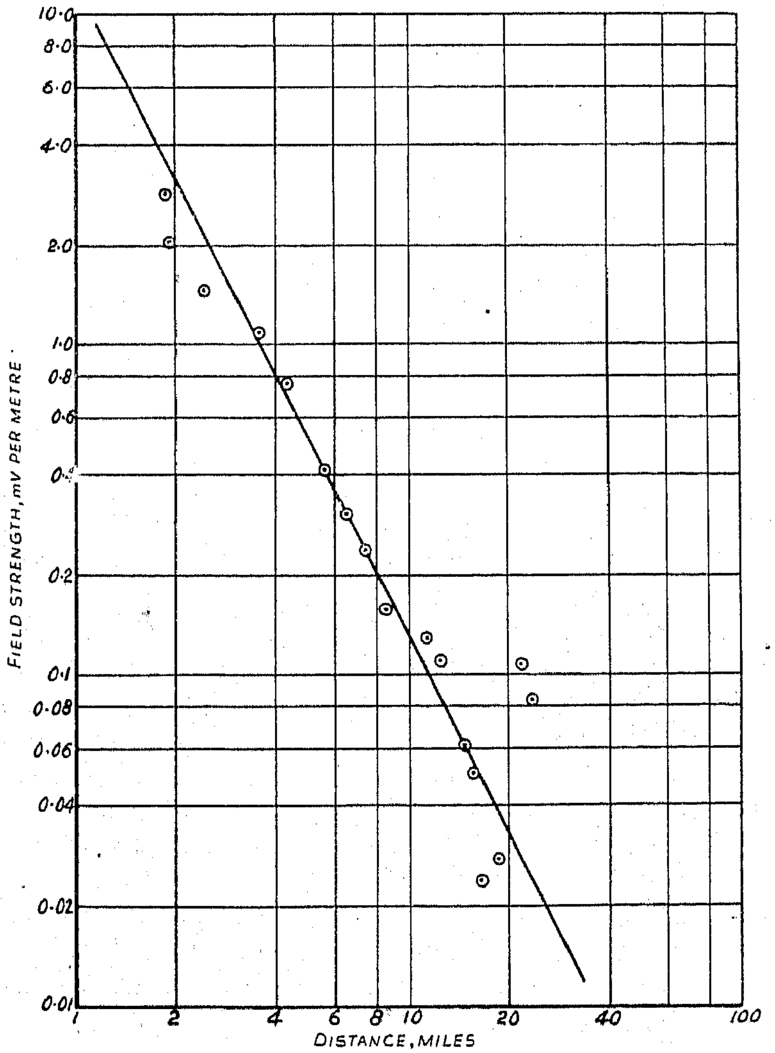

Fig. 3.—Graph showing field strength in N.W. direction plotted against distance.

Teddington transmitter, λ = 3 m., vertical polarization.

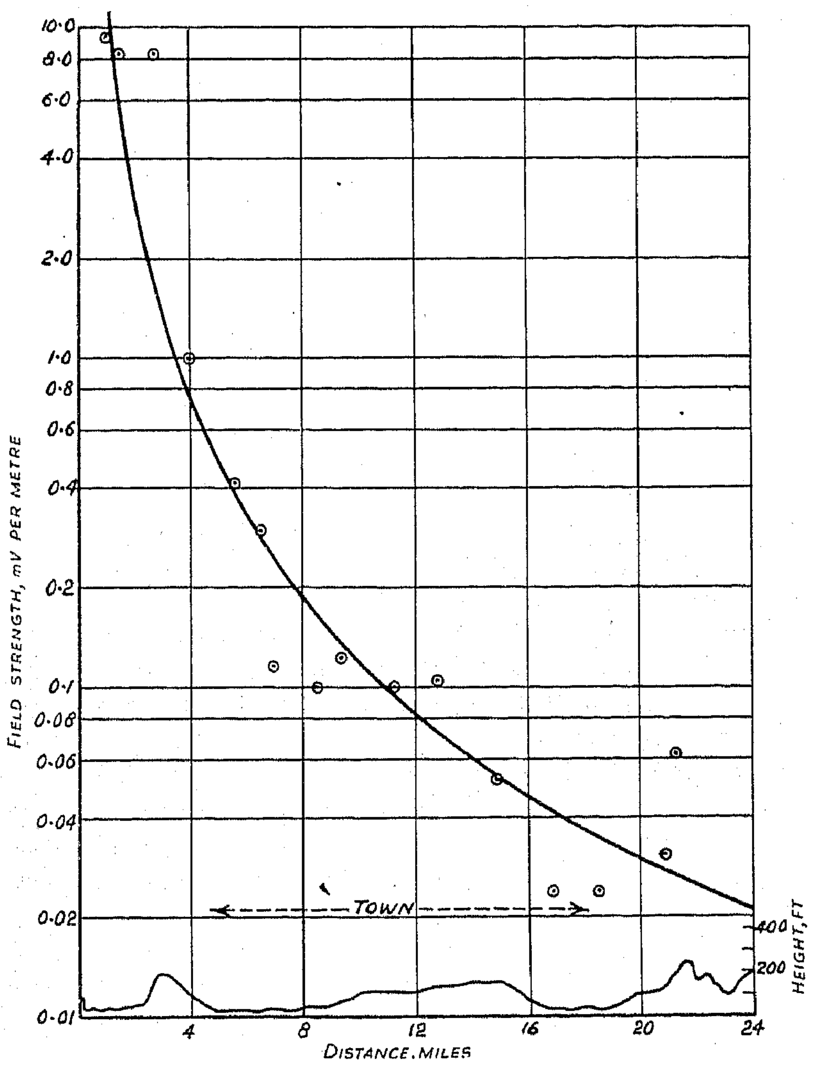

Fig. 5.—Graph showing field strength in N.E. direction plotted against distance.

Teddington transmitter, λ = 3 m., vertical polarization.

EXPERIMENTAL PROCEDURE AND RESULTS

Observations were made of the relation between field strength and distance in eight radial directions from each transmitter. The majority of the measurements were made within optical range up to distances of 20–40 miles. Fig. 2 gives the results obtained on a wavelength of 3 m. in the direction north-west from Teddington. The contour in this direction, which is shown at the bottom of the Figure, remains approximately level except for distances over 10 miles from the N.P.L. transmitter. Over at least the level portion of the run the experimental points lie close to the full line, which gives the field strength computed from relation (6) on the assumption of 100 watts radiation from the aerial, determined by means of the small dipole coupled to the transmitting aerial. The results are shown in a slightly different form in Fig. 3, in which the field strength and distance are both plotted on logarithmic scales. The full line again gives the field strength according to relation (6) for 100 watts of radiated power. This Figure shows clearly that, over practically the complete distance observed, the field strength was approximately inversely proportional to the square of the distance between the transmitter and the receiver. The results obtained on the same wavelength but in the southerly direction from Teddington are plotted in Fig. 4, as is also the theoretical curve for 100 watts radiation. The experimental points again lie close to the theoretical curve. The direction due south of Teddington passes through the cutting in the North Downs between Box Hill and Ranmore Common. An observation was made slightly off the south line from Teddington near the top of Ranmore Common (at a height of 600 ft. above mean sea-level) in order to determine the effect of the elevation of a receiving site. The field strength measured on this site is given by the asterisk in Fig. 4 and the appropriate contour in the vicinity by the dotted line at the bottom of the diagram. It will be seen that an increase in receiver-site elevation results in a correspondingly large increase in received signal. Fig 5 gives the results obtained across London from Teddington with the same wavelength and power. Care was taken that the observations in London were made only on open sites in public parks and recreation grounds. When this precaution is taken, it is evident that there is no large increase in attenuation on passing over densely populated areas.

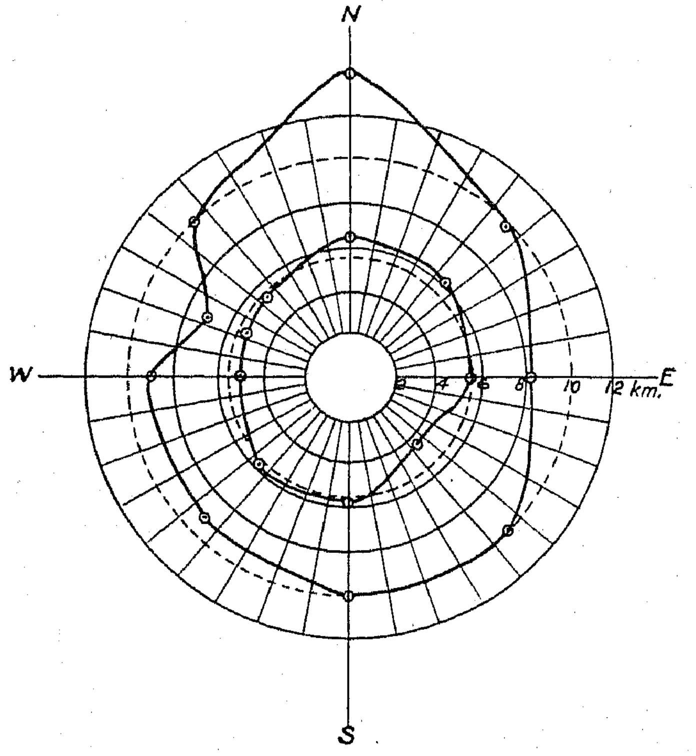

Fig. 6.—Field-strength contours of Teddington transmitter on a wavelength of 3 m., for field strengths of 1 000 and 300 μV per metre.

— — — — Theoretical contours.
———— Measured contours.

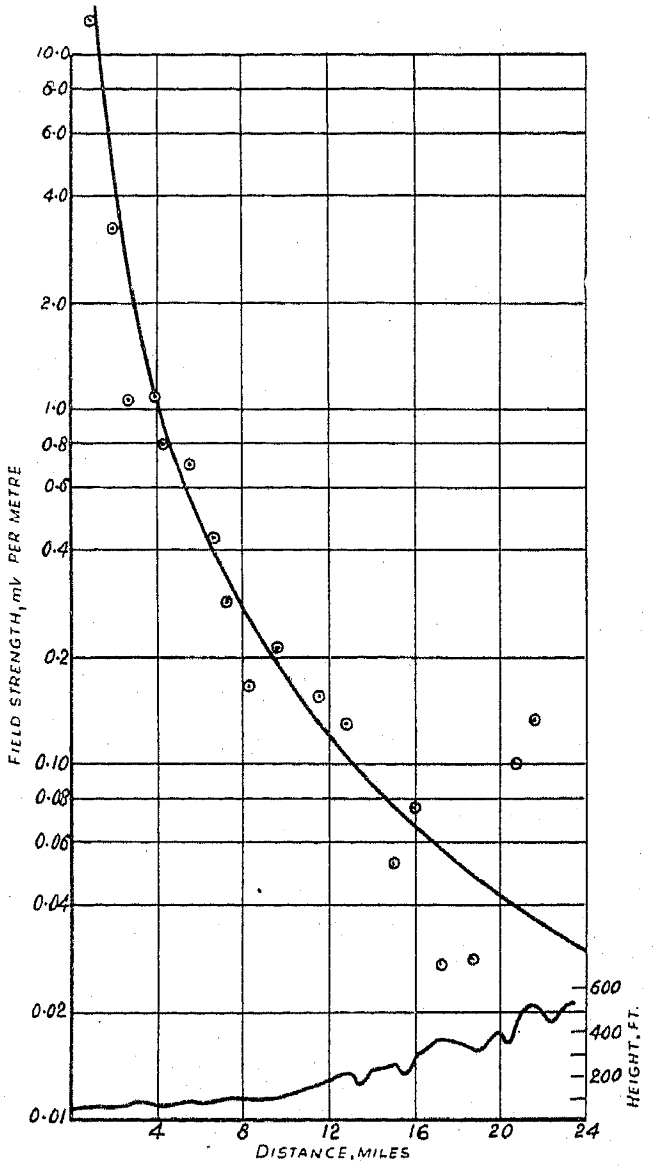

Fig. 7.—Graph showing field strength in N.W. direction plotted against distance.

Teddington transmitter, $\lambda = 2 \cdot 1$ m., vertical polarization.

Contours of constant field strength can readily be prepared from the measurements made on a series of radial runs carried out in the manner described above. The full lines joining the circles in Fig. 6 give the distance from the transmitter in any direction for field strengths of 1 000 and 300 μV per metre respectively. The dotted circles give the distances for these two field strengths on the assumptions (*a*) that the radiated power is 100 watts, and (*b*) that the law of propagation along the ground of 3-metre waves is as given by relation (6). As would be expected, the measured contour for the lower field strength and, therefore, at the greater distance, is not so nearly circular as the contour obtained near the transmitter.

The results obtained in a series of radial runs from Teddington on a wavelength of 2 m. were closely similar to those for a wavelength of 3 m.; for example, the experimental points plotted in Fig. 7 which correspond to the N.W. direction show that the field strength on the shorter wavelength is inversely proportional to the square of the distance and that it agrees approximately with that given by the full-line curve computed in accordance with relation (6). The value of radiated power determined by the small dipole near the transmitting aerial was in the region of 100 watts, for which the full-line curve in Fig. 7 has been drawn. The run made across London on a wavelength of 3 m. was similar to those in the other directions. On 2 m., however, the field strength at any site in London was always appreciably less than that obtained at a site at the same distance in any other direction from the transmitter. This can be seen from Fig. 8, in which the theoretical curve for 100 watts radiation is again shown by the full line. The dotted-line curve, to which the experimental points lie reasonably close, gives a field strength inversely proportional to the square of the distance but everywhere approximately 6 db. lower than that computed from the aerial radiation. The low field-strength in this direction, therefore, could be due to lack of uniformity in the radiation from the aerial in all directions. Field-strength measurements made in London on radiation from the Brookmans Park aerial on a wavelength of 2 m., however, gave values also small compared with those in other directions, so that it would appear that there is increased attenuation on a wavelength of 2 m. when passing over towns.

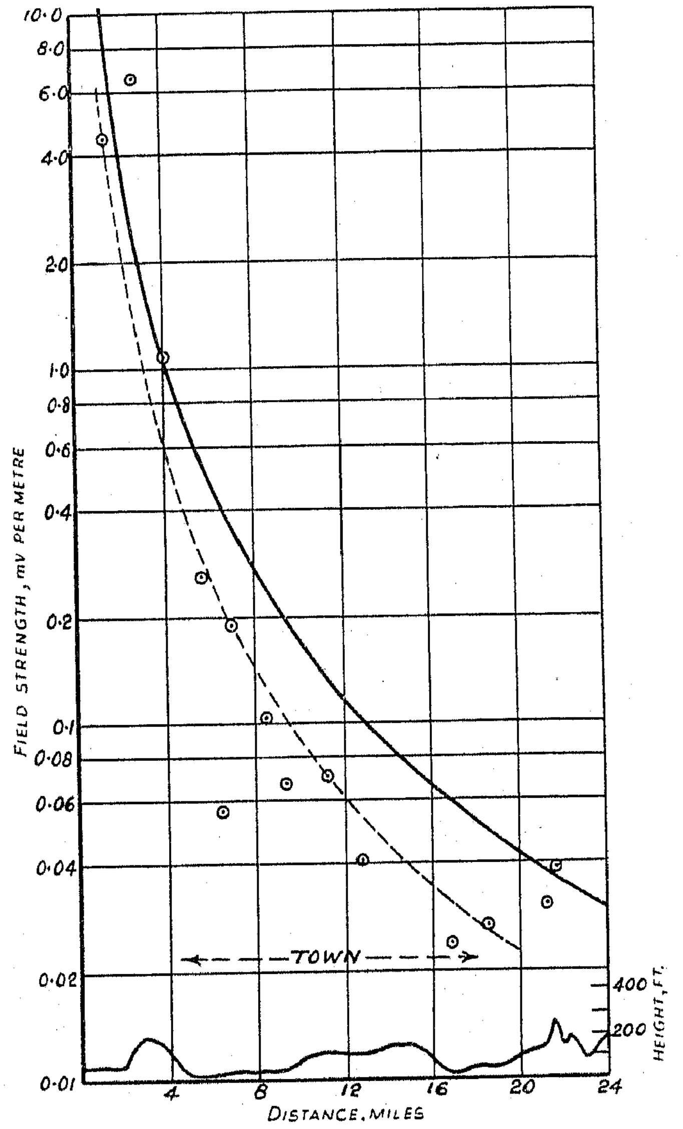

Fig. 8.—Graph showing field strength in N.E. direction plotted against distance.

Teddington transmitter, λ = 2·1 m., vertical polarization.

The results obtained in the direction of London from Brookmans Park on 2-m. wavelength are shown in Fig. 9. They are particularly interesting in that in addition to indicating the same increase in attenuation in London as was observed with the Teddington transmitter, the elevation of the receiver site beyond London becomes such that conditions approximate to that shown diagrammatically in Fig. 1(*a*). The result of the two reflected rays is evident in the large increase in signal strength above the theoretical value for one reflected ray, for distances corresponding to high receiver sites on the North Downs. The small dipole near the transmitting aerial at Brookmans Park indicated a radiated power of 60 watts, for which the full-line curve in Fig. 9 has been computed. A typical example of the results obtained in the other directions from this transmitter is given by Fig. 10 for the direction north-west of Brookmans Park. In this case there appears to be no excessive attenuation, the theoretical curve passing reasonably well through the mean of the experimental points.

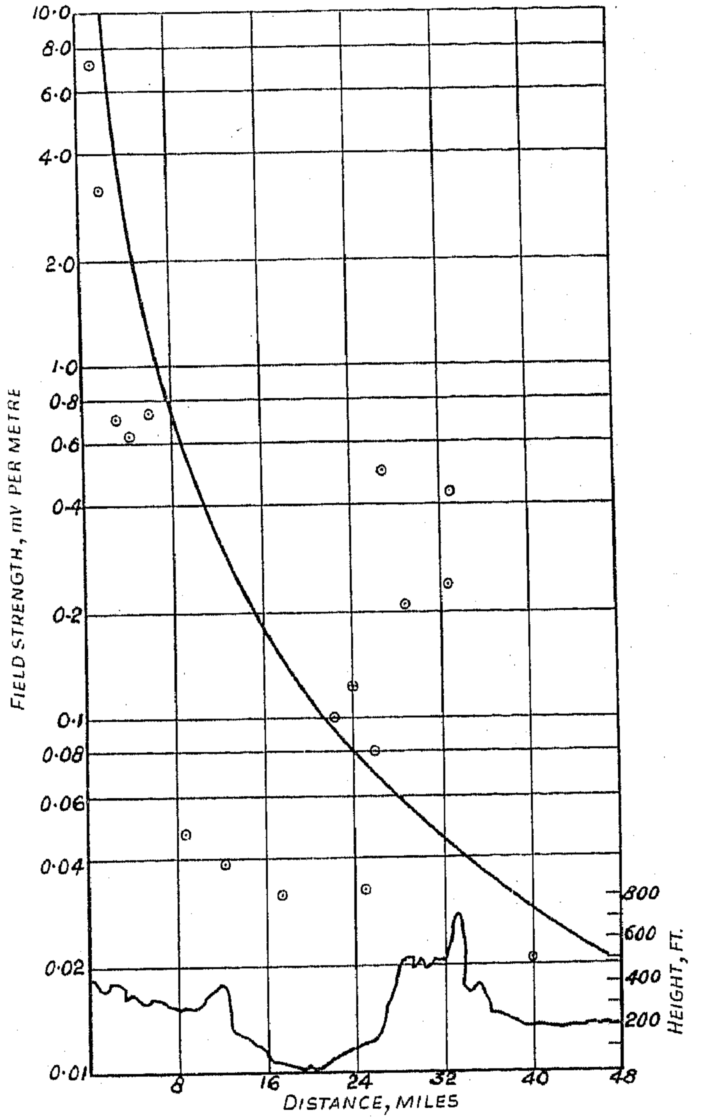

Fig. 9.—Graph showing field strength in S. direction plotted against distance.

Brookmans Park transmitter, λ = 2·1 m., vertical polarization.

The above results indicate that relation (6) gives for both Teddington and Brookmans Park transmitters a field strength which agrees reasonably well with that found in practice for wavelengths of 2 m. and 3 m. This is particularly striking when it is remembered that according to relation (6) the field strength for a given distance is proportional directly to the transmitter height, and that this varied from 60 ft. at Teddington to 230 ft. at Brookmans Park. A direct test was made to determine whether the field strength at a good open site was proportional to the height of the receiver as required by relation (6). The observations were made in the centre of a large field on a farm near Colnbrook, the terrain between Teddington and the receiver—a distance of 8 km.—being particularly level and free from large concentrations of buildings. The results obtained on a wavelength of 3 m. for both vertically and horizontally polarized waves are given in Fig. 11. The experimental points for each type of linear polarization lie close to the straight line which shows the proportionality between field strength and receiver height. The results obtained in the radial runs from the transmitter, and the above experiments, show that the field strength from a given transmitter is inversely proportional to the square of the distance of the receiver from the transmitter and directly proportional to the receiver height. Because of the reciprocity of the propagation the field strength must also be proportional to the transmitter height. The form, therefore, of the expression for field strength in terms of distance, transmitter height, and receiver height must be similar to that given in relation (6). This relation must give the actual field strength, however, when it is remembered that the average field strength deduced theoretically from relation (6) and the aerial current (derived

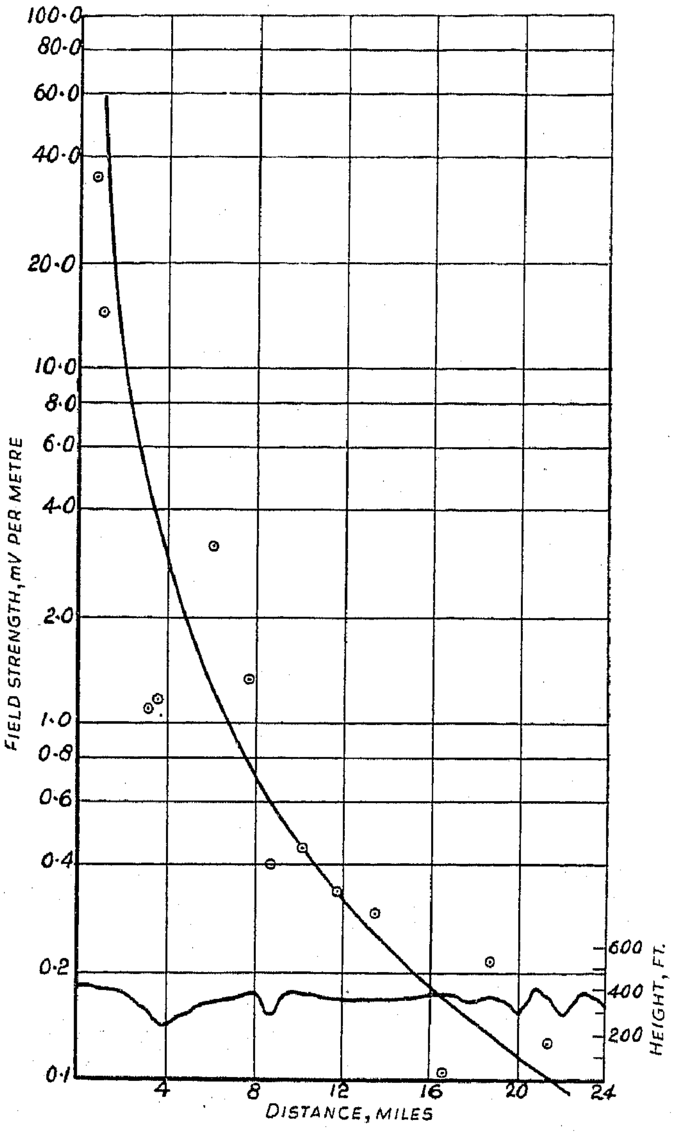

Fig. 10.—Graph showing strength in N.W. direction plotted against distance.

Brookmans Park transmitter, $\lambda = 2 \cdot 1$ m., vertical polarization.

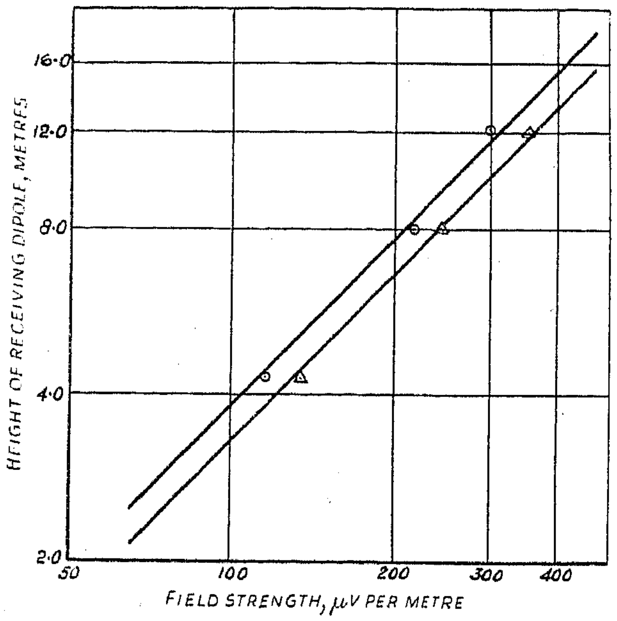

Fig. 11.—Relation between field strength and receiver height.

$\lambda = 3$ m.
⊙ = Vertical polarization.
△ = Horizontal polarization.

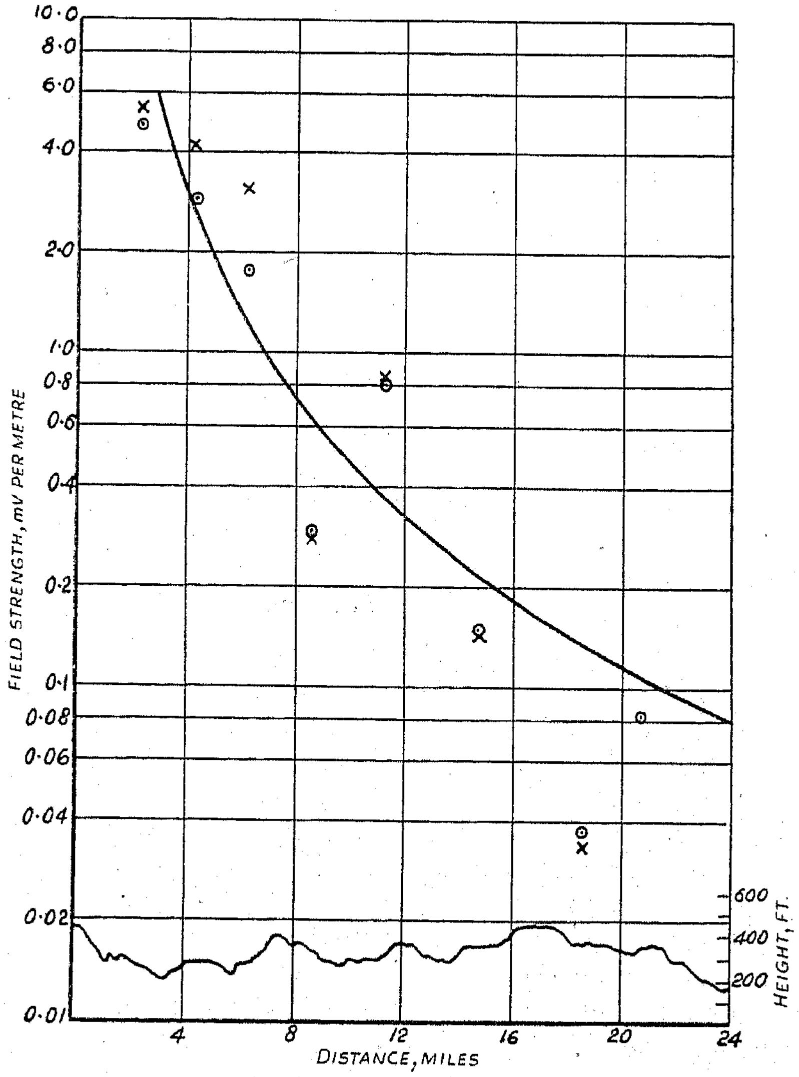

Fig. 12.—Comparison of propagation of horizontally and vertically polarized waves.

Brookmans Park transmitter, $\lambda = 2 \cdot 1$ m.
⊙ Vertical polarization.
× Horizontal polarization.

from the small dipole current) agreed with that found in the radial runs from both transmitters. Corroboration that the field strength is proportional to the height of the receiving aerial was obtained in measurements on a wavelength of 2 m. using vertical polarization. An investigation of horizontally polarized waves could not be made, as the 2-metre aerial at Teddington cannot be rotated into the horizontal position.

It is of interest to note that in Fig. 11 the ratio of the field strengths for the two straight lines and a given receiver height is 1·15, which was—within the limits of experimental error—equal to the ratio of measured currents in the aerial.

It follows, therefore, that for a good open receiving site the vertical field strength at a given height from a vertical transmitting aerial is the same as the horizontal field strength in the same receiver position from the same aerial when rotated into the horizontal position. This means that on a wavelength of 3 m. and for the transmitter and receiver heights used in the above experiments, the propagation characteristics of vertically and horizontally polarized waves are identical. This condition is implicit in relation (6), as this relation should hold for both polarizations if the earth's surface can be assumed to be plane and the reflection at the ground of an optical nature. The similarity in the propagation characteristics of vertically and horizontally polarized waves on ultra-short waves is shown by the results given in Fig. 12. These results were obtained by measuring the field strength at a series of positions along the direction due north of Brookmans Park on a wavelength of 2·1 m. At each receiving site the values of field strength in the vertical and horizontal directions were measured when the transmitting aerial was vertical and horizontal respectively. The experimental results for both types of polarization agree with one another so closely that there can be little difference in the propagation characteristics of the types of radiation. It must be emphasized that all observations on the comparison between vertically and horizontally polarized waves were made on as clear and open receiving sites as possible within optical range of the transmitter. It cannot be assumed, therefore, that these characteristics will remain the same in the shadows of hills or other obstacles, or beyond the optical range of the transmitter.

Continuous observations for periods of 24 hours have been made on several occasions on the 3-metre transmitter at Teddington, the receiver being at Ditton Park at about 10 miles' distance. The variation in field strength was never very large, nor did it fluctuate rapidly or with large amplitude. There did, however, appear to be some correlation between field strength and the shade temperature at the receiving station.

CONCLUSIONS

The theoretical curves, with which the experimental results agree fairly well, were derived on the assumption that the earth's surface is plane. The effect of taking the curvature into account is shown in Fig. 2, in which the full-line curve corresponds to the case of a plane earth, and the dotted curve to the actual earth's curvature. It will be seen that the experimental results agree much more closely with the theoretical curve for a plane earth. The following conclusions, therefore, can be deduced from the above experimental investigation with elevated transmitting and receiving aerials:—

(*a*) For distances within optical range of the transmitter the electric field strength on a wavelength between 2 m. and 3 m. is given sufficiently accurately in practice on the assumption of a plane earth and optical reflection at the earth's surface.

(*b*) For distances up to the optical range of the transmitter and over a reasonably smooth earth's surface the propagation characteristics of vertically and horizontally polarized waves are identical.

(*c*) For grazing incidence the field strength for either polarization is inversely proportional to the square of the distance between transmitter and receiver and directly proportional to the product of transmitter and receiver heights.

(*d*) In town the ratio of the measured to the theoretical field strength, assuming a flat earth, appears to be less on a wavelength of 2 m. than on 3 m.

(*e*) No fading in excess of ± 3 db. has been observed for distances up to the optical range of the transmitter.

ACKNOWLEDGMENTS

The work described in this paper was carried out as part of the programme of the Radio Research Board, and thanks are due to the Department of Scientific and Industrial Research for granting permission to publish it.

The authors are also indebted to the General Post Office for the loan and operation of a transmitter; and to the British Broadcasting Corporation for permission to install the transmitter at Brookmans Park. Messrs. Drewe and Goodyear, of the British Broadcasting Corporation, were particularly helpful. Dr. Smith-Rose's advice during the progress of the investigation is gratefully acknowledged. Mr. C. G. Carter assisted with the transmissions, and Mr. B. J. Byrne with the measurements.

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[The discussion on this paper will be found on page 159.]

RADIO DIRECTION-FINDING ON WAVELENGTHS BETWEEN 2 AND 3 METRES (100 to 150 Mc./s.)*

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(*Paper received* 19*th June*, 1939; *read before the* WIRELESS SECTION 3*rd April, and before the* HAMPSHIRE SUB-CENTRE 22*nd May*, 1940.)

SUMMARY

This paper describes a preliminary investigation of radio direction-finding on wavelengths between 2 m. and 3 m. (100 to 150 Mc./s.) with the aid of instruments fitted with rotating aerial systems similar to those used in earlier work in the band 6 m. to 10 m. (30 to 50 Mc./s.). The sensitivities of the loop and Adcock direction-finders used are such that bearings with a swing of ± 5° can be obtained with field strengths of 20 and 40 μV per metre respectively. The reciprocal error of the instruments has been reduced to 1°, and the polarization error can be kept below 5° for angles of incidence and polarization to the vertical of 60°, although readjustment of the compensation arrangement is required to maintain this over an appreciable wave-band. The two direction-finders have been operated at various distances up to 30 miles from an experimental transmitter developing 100 watts on a wavelength of 3 m., and the average errors varied from about 10° at 1 mile to 3·5° at 20 miles with a vertical transmitting aerial. These errors are somewhat larger than the corresponding values found for the longer-wave band of 6 m. to 10 m. (30 to 50 Mc./s.). When an attempt was made to use a direction-finder inside a wooden hut, the observations were found to be subject to an octantal error of 2° to 5° amplitude, the value increasing as the wavelength was reduced. This error was found to be due to reflection effects from the walls of the hut, and experiments made with various wooden boards showed that it depended upon the nature of the wood and direction of the grain. A synthetic material with no grain direction was found to have only a small effect.

(1) INTRODUCTION

A previous paper[1] contained a description of experimental work conducted on wavelengths between 6 m. and 10 m. (30 to 50 Mc./s.), principally with the aid of a rotating-loop direction-finder. Further investigations in this band have been carried out, and the results will be described in other papers now in course of preparation. It was considered desirable at the same time, however, to extend the investigation with the view of ascertaining the possibilities of direction-finding at the shortest wavelengths, and of studying any new phenomena which might be encountered in the course of this extension. In another portion of its work, the Radio Department of the National Physical Laboratory has been studying the propagation of ultra-short waves, with particular reference, recently, to the band 2 m. to 3 m. (100 to 150 Mc./s.). Certain experimental transmitters having been made specially available for this work, it was considered expedient to inaugurate direction-finding experiments also in this wave-band. The present paper describes the results so far obtained in this particular phase of the investigation.

Previous direction-finding investigations in this waveband have been described by E. Harmening and W. Beuermann.[2] With a direction-finder of the rotating "H" Adcock type operating on a wavelength of 3 m., bearings were obtained on aircraft transmitters at ranges between 10 and about 150 miles, the maximum error during a series of flights being 3°.

(2) DEVELOPMENT OF DIRECTION-FINDING APPARATUS

The direction-finders used in this investigation are of the rotating-loop and spaced-aerial types developed on the lines of those already described for the wavelengths 6 m. to 10 m. (30 to 50 Mc./s.). In each case the aerial is rigidly attached to the frequency-changer, which incorporates a push-pull detector and a separate radio-frequency oscillator. This unit rotates on a turntable, and the output at intermediate frequency is passed down a screened transmission line to a suitable receiving amplifier fixed in position on the ground below. With the reduction in the working wave-band to 2–3 m. (100 to 150 Mc./s.), it was considered that, under present conditions, adjacent-channel selectivity could safely be sacrificed in favour of other advantages. These include increased ease of tuning, freedom of interaction between oscillator and detector circuits, freedom from the effects of oscillator drift, and the ability to deal with frequency-modulated transmissions. The apparatus was therefore adapted to operate with an intermediate frequency of 10 Mc./s., at which frequency the same amplification could be obtained as at the frequency of 2 Mc./s. formerly employed, but with a much broader band-width giving the advantages mentioned above.

Various arrangements of aerial circuits have been used, and a detailed investigation is still required in order to decide which are the most satisfactory arrangements. The experimental loop direction-finder incorporated a symmetrical tuning condenser in the top limb of the square loop, while the lower limb was inductively coupled to a screened secondary circuit connected to the input of the receiver. In the case of the Adcock direction-finder, difficulty has been experienced in balancing the aerial-transmission line circuit, and in general the reciprocal error varies with the working frequency. There are also indications that the transformer screen between the aerial and secondary circuits is not completely satisfactory, since rotation of the primary coil and screen relative to the secondary coil varies the reciprocal error. Various experimental expedients have been adopted in adjusting both the reciprocal and polarization errors to low values for carrying out investigations over restricted frequency-bands.

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* Official communication from the National Physical Laboratory.

(3) STUDY OF INSTRUMENTAL FEATURES

(a) Operation

In the study of the instrumental performance of both loop and Adcock direction-finders it has been found convenient in the past to utilize an elevated transmitter of the type described elsewhere,[3] and fitted with a dipole aerial which can be so oriented as to give downcoming waves with various angles of polarization. This system has proved very satisfactory for work at longer wavelengths, but in attempting to use it in connection with the present investigations, certain difficulties were encountered due to the fact that the component aerials were each rather more than a wavelength long, and also that the transmitter box itself was an appreciable source of radiation. The experimental arrangements were considerably improved by removing the transmitter itself from the top of the tower to the ground, and connecting it by a balanced flexible wire transmission line to a short dipole aerial system on the tower. As a result of these experiments, a modified form of elevated aerial transmitter is in course of construction for use in the continuation of the study of polarization errors at very short wavelengths.

When using either the loop or the spaced-aerial

Table 1

RESULTS OF OBSERVATIONS ON THE TEDDINGTON TRANSMITTER WITH LOOP AND ADCOCK DIRECTION-FINDERS (WAVELENGTH ≃ 3 M.)

Site		From transmitter		Bearing data		
Ref. No.	Location	Distance	True bearing	Receiver in use	Error	Swing (±)
		miles	deg.		deg.	deg.
45	Bushy Park (Hampton Hill)	0·75	294	Loop	+ 3	2·5 NS*
				Adcock	+ 6	1·0 NS
47	Bushy Park (100 yd. from gasworks)	0·75	106	Loop	+30	6·0 NS
				Adcock	+ 9	15 NS
43	Hampton Court	1·0	191	Loop	+12	3·0 NS
				Adcock	+ 6	3·0 NS
48	Ham Common	2·0	55	Loop	+ 8·5	4·0 NS
				Adcock	+ 8·0	3·0 NS
58	Richmond Park (near Robin Hood Gate)	3·5	67	Loop	− 5·0	6·5 NS
				Adcock	− 6·0	10 NS
35	Richmond Park (near Sheen Gate)	3·75	50	Loop	+ 3·5	3·0 NS
				Adcock	+ 4·0	4·0 NS
54	Kempton Park	4·5	265	Loop	+ 9	2·0 NS
37	Raynes Park	4·5	104	Loop	+ 7	0·5 NS
				Adcock	+11	1·5 NS
39	Claygate	4·5	183	Loop	− 5	2·5 NS
				Adcock	− 3	5·0 NS
40	Hersham	4·5	216	Loop	+12	1·5 S
				Adcock	+ 8	2·0 NS
31	Bedfont	4·5	292	Loop	− 2	2·5 NS
				Adcock	− 1	2·0 NS
59	Queen Mary Reservoir	5·0	265	Adcock	0	1·0 NS
21	Hatton	5·0	312	Loop	+ 5	2·0 NS
				Adcock	+ 5	2·5 NS
41	Lower Halliford	5·0	257	Loop	+10	2·5 S
				Adcock	+ 7	3·0 NS
55	East Bedfont	5·0	293	Loop	+ 2	1·0 NS
19	Sunnymeads	10·5	292	Adcock	+ 4	5·0 S
50	Pinewood	13·5	318	Adcock	− 5	4·0 S
51	Fulmer	14·0	317	Adcock	− 5	4·0 S
10	Dorney Common	14·5	293	Adcock	− 1	8·0 S
52	Hedgerley	16·0	317	Adcock	+ 4	8·0 S
53	Beaconsfield	17·0	316	Adcock	+ 5	9·0 S
2	Hedsor	18·5	307	Loop	− 1	6·5 S
4	Coleshill	20·5	324	Loop	− 5	2·5 S
3	Tylers Green	21·5	315	Loop	+ 5	10 NS
5	Bovingdon	22·0	339	Loop	+ 4	5·5 S
56	Hemel Hempstead	24·0	350	Loop	+ 1	12 S
57	Luton	31·0	354	Loop	+11	20 S

* S = silent minimum, NS = non-silent minimum.

direction-finder, it is necessary to take precautions as to the disposition of the observer, telephone leads, etc., similar to those described in connection with the work on longer wavelengths from 6 m. to 10 m.[4] In addition, trouble has been encountered due to currents induced in the metal scale used on the tripod supporting the frequency-changer and aerial. In the presence of horizontally polarized waves, touching this scale was found to alter the observed bearing by 2 to 3 degrees. As was the case on the longer wavelengths, it is necessary to locate the operator in a fixed position below the aerial and also to keep the immediate vicinity of the set clear of persons and obstacles of dimensions comparable with the wavelength.

(b) Performance

The sensitivities of the loop and Adcock receivers are such that bearings with a swing of ± 5° are obtainable with field strengths of 20 and 40 μV per metre respectively.

With care in operation and setting of the compensating adjustments, the reciprocal error of the direction-finders may be kept below 1° over the whole wave-band from 2 m. to 3 m. The spaced-aerial instrument shows a marked variation of polarization error with change of wavelength, similar in form to that already observed on the wavelength band of 8 m. to 10 m. At an angle of incidence of 60°, and with an angle of polarization of 60° to the vertical, errors up to 20° are obtained. Under these conditions, however, with the aerial systems used, the errors can be kept down to about 5° over restricted wave-bands such as 2·85 m. to 3·0 m. (100 to 105 Mc./s.) and 2 m. to 2·3 m. (130 to 150 Mc./s.). This effect is associated with the particular aerial dimensions used, and no difficulty is anticipated in keeping the polarization error reasonably low over the whole wavelength band in future developments.

(4) FIELD OBSERVATIONS

Systematic observations have been carried out with the direction-finders described above, taken to open field sites at various distances up to some 30 miles from a 100-watt transmitter at Teddington operating on a wavelength of approximately 3 m. (100 Mc./s.). The results of these tests are summarized in Table 1. Many of the sites at which the observations were made were the same as those used in the earlier work on the longer wavelengths of 6 m. to 10 m., and the same reference numbers are used for these sites as those given in Table 1 of the earlier paper.[1]

It will be seen from this Table that the errors in the bearings observed at the different sites ranged from 0° to 30°, the loop and Adcock sets frequently giving different bearings, although care was taken to place the instruments consecutively on exactly the same spot at each site. This experience appears to indicate that the re-radiation field causing the errors contains a horizontally polarized component of greater intensity than that observed in the work at longer wavelengths. It will be noted that, as was the case at longer wavelengths, there is a tendency for the larger errors to be associated with the shorter ranges of transmission. This effect is illustrated more clearly in Table 2, which also gives a comparison between the errors experienced on the wavelengths of 3 m. and 9 m. respectively.

It was found that, in general, the observed bearing was subject to alteration with change in position of the direction-finder to a much greater extent than was observed in the 8-m. to 10-m. band. For example, at Dorney Common (site No. 10) moving the direction-finder about 10 yd. in different directions on this flat open field caused a change in observed bearing of 2 or 3 degrees. A total bearing variation of 10° was obtained over a distance of about 100 yd., although observations taken on a portable transmitter some 20 yd. away were free from this effect. At another good receiving site, Queen Mary Reservoir, the error in bearing on the Teddington transmitter changed from − 0·5° to + 1·5° when the direction-finding set was moved 40 yd. along the jetty.

At this site, also, experiments were made to ascertain the change in bearing observed on the Adcock direction-finder when the frequency of the transmitter was varied. A frequency-change of 0·1 % caused a change in bearing of about 1°, while a variation of transmitter frequency from 100 to 118 Mc./s. produced errors in bearing ranging from + 0·5° to + 2·5°.

Table 2

VARIATION OF ERROR WITH DISTANCE FROM THE TEDDINGTON TRANSMITTER. COMPARISON OF RESULTS ON WAVELENGTHS OF 3 M. AND 9 M.

Distance from transmitter	Mean arithmetic error	
	Wavelength 3 m.	Wavelength 9 m.
miles	deg.	deg.
0–2	11·0	5·0
2–7	6·0	2·5
7–12	6·0	2·0
12–17	3·5	2·5
17–22	3·5	1·0

Finally, bearing observations were made at Queen Mary Reservoir with the Adcock receiver while the transmitting aerial at Teddington was rotated in stages from the vertical to the horizontal position about an axis directed towards the receiver. The results are summarized in Table 3, from which it will be seen that serious errors are encountered with this experimental Adcock direction-finder when the radiation is predominantly horizontally polarized and at the high-frequency end of the band explored. Under other conditions, more typical of practical use, however, the polarization error is of the order of 5° or less [see Section (3) (*b*)].

(5) USE OF A DIRECTION-FINDER IN A WOODEN BUILDING

The work described above was carried out with transportable direction-finders set up on clear sites in the open, and the results so far discussed refer to the use of the instruments under these conditions. The previous investigations in the wavelength range 6 m. to 10 m.

Table 3

EFFECT ON BEARING ERROR OF VARIATION OF PLANE OF POLARIZATION OF EMITTED RADIATION ON VARIOUS FREQUENCIES. ADCOCK RECEIVER; RECEIVING SITE, QUEEN MARY RESERVOIR; TRANSMITTER, TEDDINGTON.

Wavelength	Frequency	Inclination of transmitting aerial							
		Vertical		30° from vertical		60° from vertical		Horizontal	
		Error	Swing (±)	Error	Swing (±)	Error	Swing (±)	Error	Swing (±)
m.	Mc./s.	deg.	deg.	deg.	deg.	deg.	deg.	deg.	deg.
2·95	101	−1·8	1·0 S*	−1·5	1·5 S*	− 4·0	3·0 NS*	−20	20 NS*
2·85	106	−0·4	1·5 S	−1·5	1·0 S	− 3·5	1·5 S	−17	15 NS
2·75	109	+2·5	1·0 S	0	1·0 NS	− 5·5	2·5 S	−37	20 NS
2·70	112	−0·8	1·5 S	−4·0	2·5 NS	− 7·0	5·0 NS	−48	13 S
2·55	117	+2·7	1·5 S	+7·5	1·5 S	+10·0	5·0 NS	+61	10 S

* S = silent minimum, NS = non-silent minimum.

have already been extended to the use of fixed direction-finders mounted on suitable tables[4] inside wooden huts free from any metal parts more than a few inches in length. In that case, careful experiments have shown that the presence of the building itself had only a small effect on the accuracy of the bearings observed with the instrument, and that this freedom from error was obtained whether the hut was in a wet or a dry condition.

When either of the direction-finders constructed for the wave-band 2 m. to 3 m. was installed on a table-mounting inside a wooden hut, about 14 ft. square, it was found that the observed bearings on a local portable transmitter were subject to an approximately octantal error of amplitude from 2° to 5° according to the precise operating wavelength within the band 2 m. to 3 m. (100 to 150 Mc./s.). The results obtained indicated that the error became zero when the direction of the arriving radiation was parallel to one of the sides or one of the diagonals of the hut. This relationship was confirmed by experiments made in another hut (10 ft. × 8 ft.) which could be rotated about a vertical axis with the direction-finder inside it. In this case, a similar octantal-error curve was obtained of somewhat smaller amplitude, the actual error being closely related to the orientation of the hut. Further experiments carried out in a hut which could be dismantled in sections, showed that the error in bearing was unaffected by removal of the roof, but was associated with the vertical sides. No correlation between hut dimensions and error amplitude on a given frequency has yet been noted.

The experiments with a portable transmitter were carried out at ranges of from 40 ft. to 400 ft. and these showed that the observed bearings in a given direction remained constant for a given frequency. It would thus appear to be possible to construct a calibration curve for each operating frequency, from which a correction could be obtained for this hut effect. It would be necessary to carry out such a calibration at frequency-intervals of about 5 Mc./s. in order to obtain a complete statement of the error characteristic in any particular direction, and the calibration would have to be made at azimuth-intervals of 5°. Using such a calibration procedure it appears that by interpolation in frequency and azimuth, corrections to observations taken on a transmitter of unknown bearing, emitting vertically-polarized waves, may be made without ambiguity to within ± 0·5°.

No direct examination has so far been made to ascertain the effect of the wooden hut on the polarization error of an Adcock direction-finder, but the tests described below suggest that this effect will not be negligible.

It having been ascertained that the walls of the wooden hut containing the direction-finder were responsible for the production of appreciable errors in the observed bearings, some experiments were made on various materials to ascertain more directly the nature of the phenomenon. Flat boards, about 3 ft. square, and of various thicknesses, were made up of several types of wood and supported in a vertical plane close to the loop direction-finder, in a line with the plane of the loop when in the position of minimum signal received from a local portable transmitter. With the plane of the board at right angles to that of the loop, a sheet of plywood ⅛ in. thick produced no perceptible errors at a distance of 4 ft. 6 in., but at a distance of 2 ft. 6 in. an error varying from 0·5° to 1·5°, depending on the wavelength, was obtained. These results, together with those obtained with other boards, are collected together in Table 4. Over the wavelength-band used in the measurements, the error was found to increase fairly steadily as the wavelength was reduced. From this Table, it is seen that the error increases in magnitude as the thickness of the board is increased, and that it is greater when the grain of the material is vertical than when it is horizontal. A composition board, ½ in. thick, of amorphous structure, produced errors similar in magnitude to those obtained from the ⅛-in. plywood sheet. Rotation of a board round a vertical axis gave a varying error effect, and this, together with the effect of a grain direction noted, suggests that the errors produced are due to the reflection of waves from the material. Naturally, the effective reflection coefficient will increase as the dimensions of the surface, whether this be a board or the side of a hut, become comparable with or larger than the working wavelength. This is borne out by the increase in error with the reduction in wavelength, as shown in Table 4, and also by the fact that in the wavelength-band 6 m. to

Table 4

RESULTS SHOWING ERROR IN BEARING PRODUCED ON A LOOP DIRECTION-FINDER BY A VERTICAL BOARD, 3 FT. SQUARE, PLACED AT A DISTANCE OF 2 FT. 6 IN. FROM THE LOOP

Material	Thickness	Direction of grain	Observed error at 2·7 m. (110 Mc./s.)	Observed error at 2·1 m. (140 Mc./s.)
	in.		deg.	deg.
Plywood	$\frac{1}{8}$	—	0·5	1·5
Plywood	$\frac{3}{4}$	—	1·75	2·25
Deal planks (1 board)	$\frac{1}{2}$	Vertical	1·5	1·0
Deal planks (1 board)	$\frac{7}{8}$		1·5	4·0
Deal planks (1 board)	1		2·0	5·0
Deal planks (1 board)	$\frac{1}{2}$	Horizontal	1·25	1·0
Deal planks (1 board)	$\frac{7}{8}$		1·0	2·25
Deal planks (1 board)	1		1·0	2·5
Deal planks (2 boards)	$\frac{1}{2} + \frac{1}{2}$	Both vertical	2·0	5·0
Deal planks (2 boards)	$\frac{1}{2} + \frac{1}{2}$	1 horizontal 1 vertical	2·0	3·5
Deal planks (2 boards)	$\frac{1}{2} + \frac{1}{2}$	Both horizontal	1·5	2·25
Fibre composition board	$\frac{1}{2}$	—	0·75	1·25

10 m. (30 to 50 Mc./s.) no appreciable errors due to wooden sheets, under similar conditions, have been detected.

The effects described above are obviously of importance in connection with the application of direction-finding at very short wavelengths, and the phenomena will be made the subject of further investigations as opportunity offers. It is evident that considerable care will be needed in designing and housing such direction-finders. Possible solutions will consist in setting the instrument inside a quasi-cylindrical wooden structure, in using a hut made of material which is free from the effects described, or in placing the aerial system completely external to the hut.

(6) CONCLUSIONS

This preliminary investigation of the possibilities of direction-finding on wavelengths of 2 m. to 3 m. has shown that there are no insuperable difficulties in the design and operation of instruments of the rotating-aerial type to an accuracy sufficient for much experimental work. In comparison with the results previously obtained in the wave-band 6 m. to 10 m., it appears that the errors due to the transmission path along the ground and due to the site and immediate surroundings of the direction-finder are appreciably increased with the reduction in wavelength. This factor may restrict the application of ground-to-ground direction-finding, while the possibilities of direction-finding on mobile elevated transmitters remain yet to be explored.

(7) ACKNOWLEDGMENTS

The work described herein was carried out as part of the programme of the Radio Research Board, and this paper is published by permission of the Department of Scientific and Industrial Research. The authors are indebted to Dr. R. R. Pearce and Mr. W. Dougharty, B.Sc., for valuable assistance in connection with the experiments described.

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[The discussion on this paper will be found on page 159.]

DISCUSSION BEFORE THE WIRELESS SECTION, 3RD APRIL, 1940, ON THE PAPERS BY DR. McPETRIE AND MISS STICKLAND (SEE PAGE 135), DR. McPETRIE AND MR. SAXTON (SEE PAGE 146), AND DR. SMITH-ROSE AND DR. HOPKINS (SEE PAGE 154).

Mr. T. L. Eckersley: The experimental and theoretical results obtained by Dr. McPetrie and Mr. Saxton are very interesting, and, if limited, give a true picture of ultra-short-wave transmission in the particular cases studied. But the paper gives, perhaps, a rather misleading idea of ultra-short-wave transmission, and illustrates rather forcibly the failure of very particular experiments to indicate the true nature of the general relations existing between the quantities under consideration.

For instance, the paper rather suggests that vertically and horizontally polarized transmissions are essentially equivalent, but it is only for a very restricted range that this is true. With great heights of the receiver and transmitter (as in working with aeroplanes) the difference in path between the direct and the reflected rays may be many wavelengths, in which case the interference fringes which occur may be quite different for horizontal and vertical polarizations. Again, the vertical and horizontal fields with the transmitter and receiver heights suitably specified, say 10 m. and 5 m., are only the same if the resistivity of the ground is high enough. Over sea, even on a wavelength of 2 metres, there is quite an appreciable difference (4·5 db.) between horizontal and vertical polarization at a distance of 16 km. On longer waves, say 10 m., the difference is even more marked (37·5 db.).

The formulae of Norton as used in the paper are definitely approximations, but of course are nearly correct within certain limits. It might be well to attempt a further physical explanation of them, and to indicate clearly the restrictions due to the approximations. The last term is the surface wave, and the first two represent the interference between the direct and reflected waves in the visual range (which for a flat earth is everywhere!). It might also be as well to point out that all the formulae for horizontal polarization can be derived from those for vertical polarization by substituting the horizontal ground reflection coefficient for the vertical reflection coefficient throughout the analysis, i.e. that the case quoted by Dr. McPetrie and Mr. Saxton is only a particular application of a more general rule. It should also be stressed that their approximation to Norton's formula for vertical polarization is only valid when

$$\frac{\dfrac{h_T + h_R}{d}\left(\kappa - 2j\dfrac{\sigma}{f}\right)}{\sqrt{\left(\kappa - 1 - 2j\dfrac{\sigma}{f}\right)}}$$

is a small quantity, and it does not hold even for very small angles of elevation when $\sigma/f \rightarrow \infty$.

The formulae are for a flat earth and are certainly restricted to the visual range. To attempt to extend them to apply to a curved earth by using a crude geometrical picture is entirely unjustified. It is still more unjustified to attempt to discredit the theory of diffraction and a curved earth by pointing to the disagreement of experiment with the predictions of this crude theory. The facts merely prove that this crude theory is wrong, which was quite obvious. If the correct full theory is used, it will be found that in this case it agrees closely with the flat-earth theory. Mr. Millington will discuss this in more detail.

It is interesting to note that the height of the receiver (about 400 ft.) does not add to the signal from the transmitter at Teddington ($\lambda = 2 \cdot 1$ m.). The 400 ft. of the receiver produces little height gain because the slope is gradual, and the ray between the transmitter and receiver does not rise much above the earth anywhere on its journey.

The paper by Dr. Smith-Rose and Dr. Hopkins confirms my belief that in surface ray direction-finding (at least on the band of frequencies used) the shorter the wavelength the greater the effect of irregularities and the more inaccurate the results become. On the other hand, the shorter the wavelength the more easy it is to obtain free-ray transmission, in which the errors can be made very small. By free-ray transmission I mean a ray which in its path does not approach the ground nearer than a distance h_0, where h_0 is a function of the earth's radius and of the wavelength used. It is proportional to $\lambda^{\frac{2}{3}}$. ($h_0 = 80$ m. for a 2-m. wave.)

I should like to know whether experiments have been made with an aeroplane under such conditions and, if so, whether the results are essentially more accurate. The errors found by Dr. Smith-Rose appear to be due partly to polarization and partly to ground irregularities, in which the Adcock gives bearings as bad as or worse than those given by the frames.

The question of ground irregularities is of vital importance in direction-finding. Progress can only be made, in my opinion, by a thorough understanding of some particular case where the complete theory of ground irregularities can be worked out. This should give the necessary understanding for interpreting the experimental results.

Mr. H. L. Kirke: While Dr. McPetrie and Mr. Saxton were engaged upon their investigation we were making a series of experiments in the form of attenuation runs on various frequencies between our research headquarters in Balham and the Brookmans Park broadcasting station. We obtained a number of results which seemed to confirm the general conclusion given in their paper, namely that for waves which have travelled over the brow of a hill vertical polarization gives the greater field strength, as far as shorter wavelengths are concerned. On the longer wavelengths (7 metres) our measurements show that horizontal polarization is the better under all the circumstances of our tests. The power input to the aerial, and the power radiated, were the same for both horizontal and vertical polarization as well as for all the wavelengths used for the test.

The power radiated was checked by plotting ϵd (field strength × distance) against d; if the power radiated is

Table A

Location	Distance		Frequency (Mc./s.)						
	miles	km.	37	40	45	50	55	60	64
Battersea Park	1·99	3·2	+ 0·7	+ 6·6	+ 9·1	+ 8·5	+ 6·3	+ 4·0	+ 1·3
Hyde Park	4·1	6·6	+ 5·0	+ 1·2	+ 11·6	+ 3·9	+ 2·6	+ 2·6	+ 3·2
Regents Park	5·96	9·6	+ 10·8	+ 5·4	+ 9·3	+ 8·4	+ 4·3	+ 2·4	+ 2·4
Hampstead Heath	8·6	13·8	+ 8·1	+ 2·4	+ 4·3	+ 3·4	+ 5·5	+ 6·7	+ 6·8
North Finchley	11·25	18·0	+ 1·0	+ 0·6	+ 0·3	+ 7·1	+ 4·0	− 0·7	− 3·9
Barnet Green	14·7	23·5	+ 6·4	+ 1·7	+ 0·3	+ 4·7	+ 7·0	+ 4·3	0
Brookmans Park	19·9	32·0	+ 9·2	+ 5·6	+ 5·7	+ 10·0	+ 5·2	− 3·3	− 9·9

constant the value of ϵd for $d = 0$ should be the same in all cases and should correspond with the value obtained from the formula $\epsilon_0 d_0 = 377\, hI/\lambda$. This method has been used in all cases of medium-wave measurement and is a check on the transmitter, transmitting aerial and transmitting site.

Table A gives ratios of horizontally to vertically polarized fields, expressed in decibels.

Mr. G. Millington: Presumably the reflection-coefficient curves given in the paper by Dr. McPetrie and Miss Stickland are meant to be taken in conjunction with the rest of the paper, in which case it would have been better to treat the problem afresh on its own merits, rather than make it conform with a convention already adopted for smaller angles of incidence. When dealing with nearly grazing incidence, it is physically simpler and mathematically more convenient to work with the angle of elevation. The authors do so in effect in considering the variation of the reflection coefficient with the angle of incidence θ. For the smallest value of θ they use, namely 86°, $\sin^2\theta = 0{\cdot}995$, and the error made in putting $\sin^2\theta = 1$ and $\cos\theta = 0$ in their equations (1) and (2) would be of the order of 1 in 1 000, while the derived equations (3) to (6) would become much less cumbersome.

With regard to the method of plotting the curves in terms of the real and imaginary parts of the reflection coefficient, it will be seen that the origin of co-ordinates is a long way from the figures to the right-hand side, so that the graphical method which the authors suggest for determining the magnitude and phase angle is not very practicable in this case. In computing signal-strength/distance curves, one is often concerned with functions of the type $1 - |R|$ rather than with the reflection coefficient R itself, and as $|R|$ is of the order of unity the use of the curves as given would imply the determination of a small quantity as the difference of two relatively large but nearly equal quantities. It is therefore desirable, in the interests of accuracy, to manipulate the analysis in such a way as to present these small quantities directly, and it is more convenient in this connection to derive certain other curves related to the reflection coefficient (which cannot be discussed here) rather than the ones given in the paper.

It is interesting to note that at the end of the paper the authors use asymptotic forms of the propagation equations in which the reflection coefficient has disappeared explicitly, as the angle of elevation has been assumed to be small and has been expressed as $(h_T + h_R)/d$. Thus apparently the reflection-coefficient curves are not used at all in computing the propagation curves in the later part of the paper and in the accompanying paper by Dr. McPetrie and Mr. Saxton.

The inference in this latter paper, that the theoretical flat-earth formula gives a signal-strength/distance curve which agrees better with the experimental results than does the curve obtained by taking into account the curvature of the earth, is quite unjustified. It is based on a curvature correction, given in equations (7) and (8), which is apparently empirical and is completely inapplicable. If the true curve for the curved-earth case is derived from the rigid diffraction analysis of the problem, it will be found to be almost identical with the flat-earth curve. This really means that the experimental results confirm the true theoretical curve, and that in this particular case the flat-earth formula happens to give a curve which is very nearly correct. Mathematically the flat-earth formula can be applied at any distance, since we can define a finite angle of elevation given by $(h_T + h_R)/d$ for use in the formula, even though the receiving point may actually be below the line of sight of the transmitter, and the angle may have no real significance in the geometry of the reflection from a curved earth. It can be shown analytically that, under certain very limited conditions, the flat-earth formula so used happens to give values very close to the true curved-earth values, even for points somewhat beyond the line of sight. The case which they have considered just satisfies the required conditions, and thus we have an analytical reason for the fact that the flat-earth curve agrees with their experimental results, i.e. because it happens to agree closely with the true curved-earth curve in the region considered.

Mr. C. Holt Smith: The paper by Dr. Smith-Rose and Dr. Hopkins gives a rather pessimistic view of the possibility of carrying out accurate direction-finding on frequencies of 100 to 150 Mc./s. Studying the results of the paper tends to give one the impression that progressing from waves of 10 m. to waves of 3 m. involves a considerable loss of accuracy, but I know that in practice under certain conditions this is not so. The loss of accuracy noticed by the authors is perhaps due in part to the fact that the equipment they used consisted of an aerial system situated comparatively near the ground; I think it probable that, had the height of the system been increased, some of the apparent objections and errors would have been at any rate lessened. There is a pointer in this direction, e.g. in the remarks at the top of page 156, where reference is made to errors due to the operator touching the scale or making some other movement.

The effect of height on direction-finding at these frequencies is worthy of considerable study, though there is little reference to this matter in the paper. It is quite conceivable, for example, that the rather large errors shown in Table 1 would be reduced were the height of the system increased, and if this were done the figures for polarization error would be very different. In the days of long-wave direction-finding the aerial system was invariably at a height above ground which was small compared with the wavelength; now that it is a wavelength or more above ground, the direct plus reflected rays produce a standing-wave system which will differ according to whether the polarization is horizontal or vertical. If, therefore, we move our aerial system up and down we can no doubt produce systems with apparently large or apparently small polarization errors.

The authors' remarks concerning the effects of the material of the buildings I find interesting, because I have had a somewhat similar experience. Using an octagonal wooden building lined with building-board I found that the chief phenomenon was not the introduction of direction-finding errors but a distortion of the polar diagram; that is to say, although the errors introduced by the building were certainly less than 1°, the shape of the polar diagram of the aerial system measured on a line perpendicular to the face of the building differed appreciably from that measured on a line through one corner of the building. In my case, contrary to the authors' experience, almost the whole of this effect disappeared when the building-board lining was removed.

Mr. W. L. McPherson: I should like to know what degree of accuracy Dr. McPetrie and Mr. Saxton consider that they reached with their field-strength measuring set; some of their experimental points are so close to the theoretical curve that apparently the error was very small, and yet in practice there is always considerable doubt, even at medium wavelengths, as to whether a field-strength measurement can be accurate to within 10 %.

As regards the question of horizontal versus vertical polarization, in one case with which I am familiar we had a transmission over sea covering a distance of 25 to 30 miles on a wavelength of about 7 m., and on the whole the horizontal polarization gave the better results. On the other hand, using 17-cm. waves we could find no difference between the results obtained with horizontal and with vertical polarization, irrespective of whether the transmission conditions were good or bad.

The possibility of getting good directional measurements at these wavelengths may be illustrated by our experience with the same 17-cm. apparatus. The transmitters and receivers in this case employed half-wave doublets and parabolic reflectors. When we put them up we made provision for moving them over a range of ± 5°; the correct adjustment was checked on several occasions, and we always came back to within 1° of the same direction. Of course, reception of a maximum signal on a combination of doublet and parabolic reflectors is not quite comparable with reception of a minimum signal on spaced aerials or a loop, since it involves an integration effect over a large surface of wave front, but it does show that better accuracy may be obtained than is indicated by the figures given in this paper. In the case of which I am speaking the distance covered was about 35 miles, and perhaps three-quarters of that was sea surface. The path was "optical," but there was of course reflection from the surface of the sea to interfere with the direct wave, and it is probable that the position of the reflectors was such as to involve very complicated diffraction effects from neighbouring buildings.

Mr. G. H. Munro: It is mentioned in the paper by Dr. Smith-Rose and Dr. Hopkins that the errors in bearing change appreciably with small changes in location, and we should therefore expect similar changes in the intensities. I should like to know to what extent the authors have tested and made allowance for this, and whether they found it possible to select by inspection sites where the effect could be relied upon not to be sufficiently serious to affect the accuracy of their results.

Mr. S. B. Smith (*communicated*): The paper by Dr. Smith-Rose and Dr. Hopkins extends our knowledge very considerably and indicates quite clearly the limiting accuracy which is to be anticipated with ground-to-ground direction-finding when using the loop and Adcock aerial. In view of the fact that well-chosen sites were used in the work, it would be of considerable interest if the authors could give figures relating to town areas.

Special applications may require that direction-finders working in the band now under discussion will have to be operated in city areas (from rooftops); and if so it would be interesting to have a few figures giving the probable statistical accuracy of a large number of observations under such conditions.

In comparing the loop and Adcock results now recorded with those given in the earlier paper, one observes that the gains due to the use of an Adcock aerial are much smaller when the equipment is working in the 2- to 3-metre band. It is hoped that the authors will be able to extend the present exploratory work in order to arrive at some explanation of the distortion of the wave front.

I have in mind measurements of the polarization at the various sites recorded in Table 1. It is quite clear from this Table that secondary fields do exist; the large number of non-silent minima gives us a clue, and it is quite probable that under some conditions an Adcock aerial may give greater errors of bearing than a loop aerial. It would be of interest to know whether the Adcock-aerial polarization balance was checked at each observation site, and whether visual calibration checks were made.

To be effective, direction-finding waves should be free radiation; in other words, the direction-finder must be worked at considerable elevations from the ground. At the same time, it would be of interest if the results given in Table 1 could be repeated with the direction-finding aerials raised 4 or 5 wavelengths above the ground.

In view of the complex nature of the problem, I have a feeling that ultimately the general research will proceed along the lines employed in studying the ionosphere.

Have the authors made any measurements of the dielectric constants of the materials used in the production of Table 4? If so, can some more precise data be given? It is assumed that the errors noted are due to non-symmetrical dielectrics in the immediate vicinity of the aerials.

The employment of rotating spaced loops may have some useful applications in this class of direction-finding work; have the authors any data comparing this type of aerial with those recorded in the paper?

The Authors (*in reply*): Mr. Eckersley takes us to task for suggesting that the propagation characteristics of short waves are identical under all conditions. It is explicitly stated, however, on page 147 in the experimental paper on propagation that "horizontally and vertically polarized waves are propagated equally *for grazing incidence* provided the transmitter and receiver heights. . . ." Mr. Eckersley's reference to great heights of transmitter and receiver are not such as to give conditions for grazing incidence, so that two polarizations should give different results. We agree with Mr. Eckersley about the condition under which Norton's formulae apply. These conditions are described in detail in the theoretical paper. We do not wish to discredit the diffraction theory in any way; in fact we state at the beginning of the experimental paper that our results are "in agreement with the diffraction theories put forward recently by Van der Pol and Eckersley." We do not state (as Mr. Eckersley and Mr. Millington appear to think) that there is any disagreement between our experimental results and the diffraction theory. What we do find is that for our experimental conditions there is substantial agreement between our results and those derived theoretically on the assumption of a flat earth—a deduction with which Mr. Eckersley and Mr. Millington both agree. It may be of interest to note that we find in practice that on ultra-short waves the effects of diffraction over obstacles such as hills* are usually more important than that due to the curvature of the earth.

We are indebted to Mr. Kirke for corroborating our results on the diffraction of short waves by hills, also for the useful results given in Table A. The method of plotting the product of field-strength and distance in order to determine the efficiency of a transmission appears to be particularly neat.

In reply to Mr. Millington, it is stated in the Introduction to the theoretical paper on propagation that the reflection-coefficient curves are given as an extension of an earlier paper the curves in which have been found to be particularly useful to us. The method adopted, therefore, is the same as that employed in the earlier paper, but later we have followed the procedure suggested by Mr. Millington, which is undoubtedly neater for large angles of incidence.

The experimental paper on propagation records the results observed with aerial heights varying from 3 m. to 80 m. Over this very considerable range of aerial heights and for distances up to those slightly in excess of the horizon, we find, as stated in the paper, that little error results if the received field is computed on the assumption that the earth is flat. This does not mean that we imply that the now well-known theory of diffraction of radio waves round the curvature of the earth is wrong, but that for many practical problems the earth may be assumed to be flat, a considerable simplification to those with insufficient time to acquaint themselves fully with the rather complicated theory of diffraction. Equations (7) and (8), to which Mr. Millington objects, have nothing whatever to do with diffraction and are deduced from pure geometry.

We are interested to note Mr. McPherson's remarks on the propagation of micro-waves. For the experimental conditions given in our paper, horizontal and vertical polarizations give the same field at the receiver. Owing to irregularities in topography, however, we have found that either polarization may give a received field greater than the other. We hope to publish these results later. The relative accuracy of measurement of field strength was about 10 %. In a recent comparison of various field-strength-measuring sets, covering a wide range of frequencies, we were surprised to find the agreement between the calibrations was best on the shortest wavelengths of about 7 m.

Both Mr. Holt Smith and Mr. S. B. Smith suggest that an improvement in accuracy will result if the direction-finder is elevated. In so far as the aerial system will be removed from certain possible sources of error—for example, the observer—the contention is justified, but if the receiver has to cover an extended wave-band and a large range in elevation of the received radiation has to be dealt with, no general improvement will occur. Improvement at certain portions of the wave-band due to the horizontal members of the aerial system being situated at a node in the horizontal field will be offset at other wavelengths where such favourable conditions do not exist.

The octagonal hut of which Mr. Holt Smith has had experience is an approximation to the ideal case of the cylindrical hut. In connection with the distortion in polar diagram due to the building board which he has observed, it is conceivable that this might be due to some light framework having diagonal members on which the building board may have been supported. In reply to Mr. S. B. Smith in a similar connection, we have at present no precise data as to how the properties of the hut walls, regarded as dielectrics, affect the magnitude of the observed errors.

No experiments have been made with direction-finders on roof-tops in urban areas, but it may be expected that large errors will occur. It is agreed that more experience is required in deciding on the relative merits of loop and Adcock receivers operating in fields nominally vertical but distorted by local and path conditions. No measurements of polarization error were made during the field tests.

In reply to Mr. Munro, some attempts have been made to correlate changes in field strength with changes in bearing errors at certain of the sites, but without success. If it is considered that the bearing errors arise owing to unwanted incoming rays radiated from certain interfering obstacles, this is not surprising. Quite large bearing changes may occur with but little or even no change in field strength.

Mr. McPherson's remarks are of interest as they indicate the accuracy of repetition likely to be obtained by direction-finders operating at very short wavelengths and utilizing the maximum lobe of some form of directional array. It seems probable that such aerial systems may have to be used as operating wavelengths are successively reduced.

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* *Nature*, 1939, **144**, p. 631.

CALCULATION AND EXPERIMENT ON TRANSFORMER REACTANCE IN RELATION TO TRANSIENTS OF RESTRIKING VOLTAGE*

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(*Paper first received* 19*th January, and in revised form* 8*th May*, 1940.)

SUMMARY

In this paper it is shown that the effective leakage inductance of transformers, which in many cases determines transients of restriking voltage, cannot be regarded as a constant, but varies very considerably with time from the start of the transient and with the frequency of the transient. In extreme cases the effect of this phenomenon may be to reduce the rate of rise to 70 %, and the first peak of restriking voltage to 50 %, of the corresponding values calculated using the power-frequency leakage inductance of the transformer. It is shown that the laws governing these variations can be calculated with reasonable accuracy from the dimensions of the transformer.

In illustration of the importance of this phenomenon in practical cases, the paper describes short-circuit site tests for the measurement of transients of restriking voltage at the medium-voltage busbars of a large substation. The work is, however, equally applicable to higher-voltage busbars.

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Appendix III. The Reactances and Capacitances of the 3-Phase Transformer Unit and of the Transformer and Cables to the Fault Point.

I. INTRODUCTION

A typical circuit in which a transformer plays a large part in determining the transient of restriking voltage is shown in Fig. 1(*a*), the conventional equivalent circuit being shown in Fig. 1(*b*). In most cases the exciting inductance of the transformer may be neglected in calculations of restriking voltage, and if this is done the simple equivalent circuit of Fig. 1(*c*) is obtained, where the inductance L_2 is that appropriate to the leakage reactance of the transformer, L_1 being that relating to the reactance of the generating plant.

In a recent E.R.A. report[1] dealing with measurements on restriking-voltage transients at a transformer substation, using the restriking-voltage indicator (R.V.I.), it was pointed out that the effective inductance per phase of the transformer determining the frequency of the transients appeared to be about 93 % of the nominal leakage inductance, the resonant frequency of the system being from 8 to 14 kc./s. Some evidence was also produced to the effect that measurements on another transformer showed this same type of reduction in effective inductance for resonant frequencies considerably higher than the power frequency.

Evans and Monteith[2] have also pointed out that for synchronous machines (to which apply somewhat the same considerations as for transformers) the negative phase-sequence reactance determining the restriking-voltage transient decreases with rise of frequency, falling linearly so that at 1 000 c./s. it has 80 % of its power-frequency value. The phenomenon was stated to be due to eddy currents, but no analysis was given showing how the effect is operative.

The present paper gives an account of field short-circuit tests on transients of restriking voltage, in which the phenomenon of variation of effective reactance of transformers was demonstrated to a very marked extent. In order to explain the results of these tests, a detailed investigation into the variation of effective transformer reactance was carried out, and as a result of this it is here shown that, so far as transients of restriking voltage are concerned, L_2 is, for any transformer, a parameter* which varies with frequency and with time from the start of the transient, and that the laws governing these variations can be calculated with reasonable accuracy from the dimensions of the transformer.

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* Official communication (Ref. G/T125) from the British Electrical and Allied Industries Research Association.

The Papers Committee invite written contributions, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Contributions (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

The short-circuit tests here reported gave the opportunity of recording transients of restriking voltage across a circuit-breaker, substantially on the 425-V busbars of a large substation, clearing 3-phase-earth faults at the circuit-breaker terminals. The conditions of the tests were specially arranged to give a short-circuit condition much more severe than that normally obtaining on the network. The 425-V busbars were fed through 1 500-kVA transformers used either singly or two in parallel, the transformers in turn being supplied from 6·6-kV substation busbars on which the fault capacity was approximately 350 MVA.

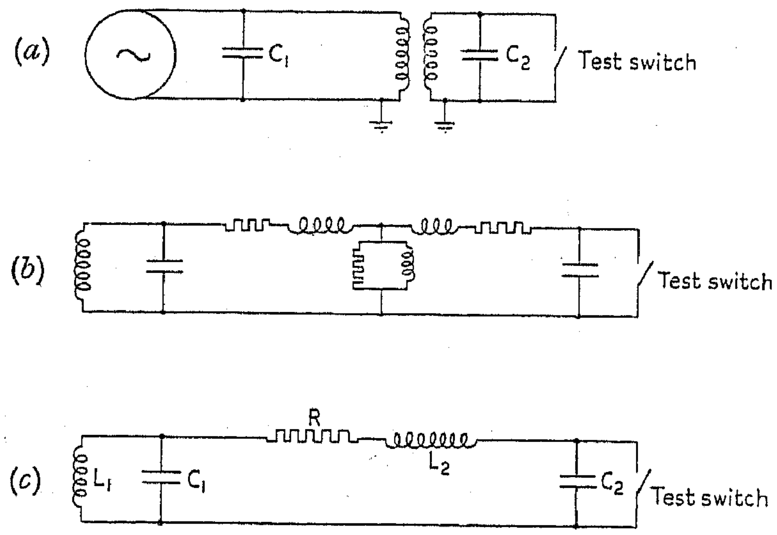

Fig. 1.—Representation of test plant with transformer.

(a) Schematic diagram of short-circuit test plant.
(b) Equivalent circuit.
(c) Simplified circuit.

Although little appears to be known of the effect of variation of rate of rise of voltage on the performance of low-voltage and medium-voltage† switchgear, it is not out of place, in the course of a survey of restriking-voltage conditions on networks such as that undertaken by the E.R.A., to include measurements at such a site, which must be typical of a majority of the situations in which high rupturing capacity is called for in medium-voltage circuit-breakers, since fault-kVA values fall very rapidly when any appreciable length of cable is interposed between transformer and busbars.

In the tests the circuit-breaker in question was connected to the substation busbars by a very short length of cable, and thus the circuit arrangement differed slightly from service conditions at the busbars. The transient of restriking voltage for a breaker on the busbars under actual service conditions is, however, calculated using the theory which the experimental results have shown to be justified.

Apart from the intrinsic value of the test data on conditions at medium-voltage busbars, the theory on which the results are explained is applicable to transformers of all sizes and voltages.

It follows from the work described in the paper that, in designing transformers for use, for example, in a switchgear-testing plant, where maximum circuit severity (i.e. highest initial reactance) is required, the copper sections used in the winding should be kept as thin, in a direction perpendicular to the leakage-flux paths, as is consistent with mechanical requirements. Conversely, in transformers for use in a network where minimum severity is required, it is advantageous to use as large copper sections as possible, and it might be worth while for designers to keep this point in mind when deciding on details within the limits set by the major features of design, e.g. efficiency, cost, etc.

II. TRANSFORMERS AS PLANT UNITS DETERMINING TRANSIENTS OF RESTRIKING VOLTAGE

The calculated transient of restriking voltage at the interruption of the circuit of Fig. 1(c) by the test switch will be of the form

$$A\left[\left\{L_2 - L_2(1 - e^{-\alpha_2 t})\cos 2\pi f_2 t\right\} + \left\{L_1 - L_1(1 - e^{-\alpha_1 t})\cos 2\pi f_1 t\right\}\right]$$

where α_1, α_2, f_1, f_2, are appropriate decay coefficients and frequencies respectively. If, as most frequently happens in practice in transformer substations,[3] f_2 is large compared with f_1, the transient up to the first peak is substantially

$$A\left[L_2 - L_2(1 - e^{-\alpha_2 t})\cos 2\pi f_2 t\right]$$

since the second term contributes very little to the total voltage over the time involved, even if L_2 and L_1 are of nearly equal magnitude.

It is found in practice that where L_2 represents the leakage reactance of a transformer, L_2 cannot be regarded as a constant, but that the voltage transient must be represented by

$$A\left[L_2' - L_2''(1 - e^{-\alpha_2 t})\cos 2\pi f_2 t\right]$$

where L_2' is a function of time, and L_2'' depends on the value of f_2, for any given transformer. An example of the variation of L_2' is shown in Fig. 2, which is a trace of an R.V.I. record showing the transient of restriking voltage on a system supplied through a transformer from a generator of zero impedance.

The extent to which these parameters L_2' and L_2'' vary from the power-frequency inductance of the transformer, and the manner in which they may be calculated from the dimensions of the transformer, are examined in the next two sections.

The experimental side of this work was carried out on a 6 600/12 800-V single-phase shell-type transformer of 1·5 % reactance at 3 700 kVA, built in 1920. The results are, however, directly applicable to modern transformers, including polyphase units, so far as positive and negative phase-sequence phenomena are concerned.

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* The term "parameter" is here used to mean those quantities relating to the circuit (e.g. resistance, inductance and capacitance) which are normally regarded as the constants of the circuit but which, under the conditions considered, must be treated as variables.

† "Medium voltage" is defined in the "British Standard Glossary of Terms Used in Electrical Engineering" (B.S. No. 205—1936) as any voltage normally exceeding 250 volts and normally not exceeding 650 volts.

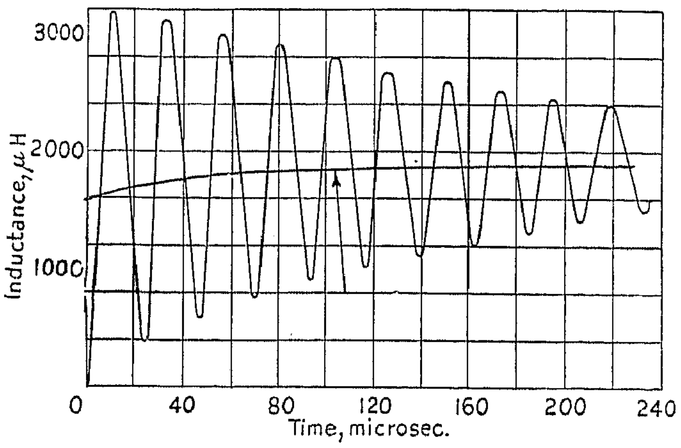

Fig. 2.—R.V.I. record showing the restriking-voltage transient of the secondary winding when shunted by 0·005 μF.

Rise of mean of envelope of oscillation (indicated by arrow) shows increase of effective inductance with time.

An extension to cover the zero phase-sequence reactance of polyphase units is made later in the paper.

III. VARIATION, WITH FREQUENCY, OF THE INDUCTANCE DETERMINING THE FREQUENCY OF THE RESTRIKING-VOLTAGE TRANSIENT

(a) Experimental Determination

The effective inductance of the single-phase transformer referred to above was obtained, over a range of frequencies from 50 c./s. to 50 000 c./s., under both short-circuit and no-load conditions, by various methods as set out in Appendix I. Conditions during these experiments were so arranged that the frequencies were predominantly determined by the simple *LC* circuit constituted by the leakage inductance of the transformer and external shunt capacitance plus the self-capacitance of the transformer. The latter quantity was estimated by two different methods. Table 1 gives, for each shunt capacitance shown in Col. 1, the resonant frequency observed by several different methods (Cols. 2, 3 and 4) and the resonant frequency (Col. 5) calculated from the shunt capacitance of Col. 1 taken with the self-capacitance of the transformer and the known power-frequency inductance of the transformer. It will be seen that the values of Col. 5 are all appreciably lower than those of Cols. 2, 3 and 4.

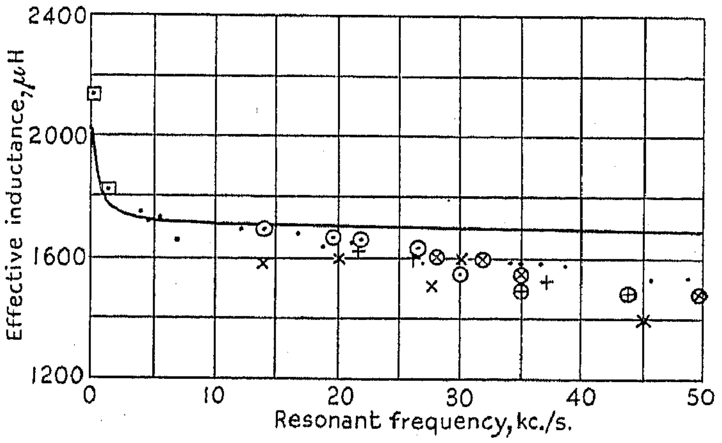

Fig. 3.—Variation of effective leakage inductance with frequency.

× Data from C.R.O. under short-circuit conditions.
⊙ Data from R.V.I. on test circuit.
+ Data from R.V.I. on isolated transformer.
· Data from variable-frequency oscillator.
☐ Data from lower-frequency measurements.
— Theoretical curve.

Table 1

TRANSFORMER RESONANT FREQUENCIES: COMPARISON BETWEEN OBSERVED VALUES AND VALUES CALCULATED USING THE POWER-FREQUENCY INDUCTANCE, ASSOCIATED WITH DIFFERENT VALUES OF SHUNT CAPACITANCE

1	2	3	4	5
Total external shunt capacitance, μF	Observed frequency, kc./s.			Calculated frequency, kc./s.
	From C.R.O. records	From R.V.I. records	Interpolated from oscillator measurements	
0·0010	57·0	57·3	56·0	48·9
0·0030	49·7	49·4	48·5	41·3
0·0050	44·8	43·4	42·0	36·4
0·0093	35·2	35·3	34·8	29·9
0·0096	34·5	35·1	34·3	29·6
0·0117	31·9	32·0	32·1	27·6
0·0138	29·9	30·2	30·0	25·9
0·0163	28·0	27·9	28·1	24·2
0·0182	27·4	26·5	26·8	23·2
0·0355	19·9	18·6	19·8	17·3
0·0754	14·2	13·7	13·8	12·2

Table 2

TRANSFORMER LEAKAGE INDUCTANCE AT LOWER FREQUENCIES BY VARIOUS METHODS

Method	Frequency, c./s.	Inductance, μH
Calculation	50	2 130
Bridge	50	2 120
Duddell oscillograms ..	50	2 130
R.V.I.	50	2 100
Bridge	1 000	1 830

From the observed frequencies of Table 1, Cols. 2, 3 and 4, and the known capacitance values, effective inductances at each frequency were calculated: these are shown in Fig. 3, together with inductance values at 50 c./s. and 1 000 c./s. obtained by other methods as set out in Table 2. It will be seen that the variation of effective inductance with frequency appears to follow a consistent law.

(b) Theoretical Calculation

At power frequencies, normal design methods* may be used to calculate the leakage reactance of the transformer, which is regarded as a constant, and it is common experience that such methods give results that agree closely with the measured values.

The leakage flux of the transformer, as calculated by these methods, may be regarded as composed of two main parts, namely that which passes through the air-gaps between the coils (the " gap flux ") and that which passes through the copper of the windings (the " copper flux "). Some of each portion also passes through the iron of the core.

It can be shown[5] that in a conducting strip subject to a uniform magnetic field pulsating with frequency $p/(2\pi)$, in a direction perpendicular to the plane of the strip, the effect of eddy currents can be regarded as that of reducing the width of the strip to a value $2d$, where

$$d = \frac{1}{k\sqrt{(2p)}}\left(\frac{\cosh 2ak\sqrt{p} - \cos 2ak\sqrt{p}}{\cosh 2ak\sqrt{p} + \cos 2ak\sqrt{p}}\right)^{\frac{1}{2}}$$

where $2a$ = width of strip,
$k = \sqrt{(2\pi\mu/\rho)}$,
ρ = resistivity,
and μ = permeability.

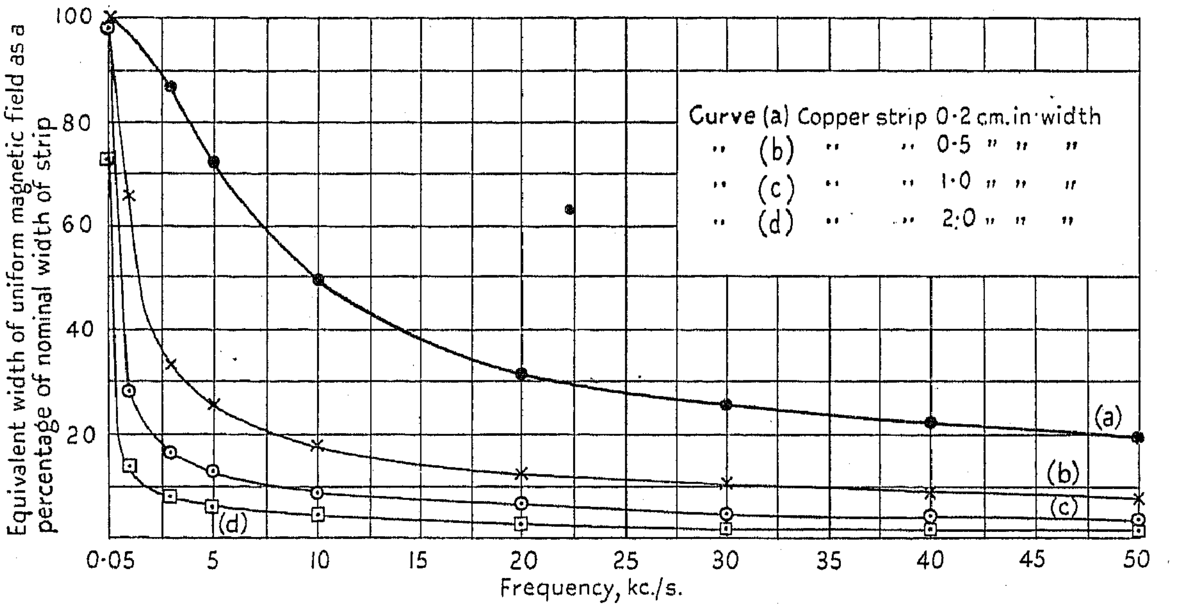

Fig. 4.—The equivalent width of uniform magnetic field as a percentage of the actual strip width, for copper strips of various widths at frequencies from 50 c./s. to 50 kc./s.

The remainder of the strip may be regarded as replaced by a strip of impermeable material of width $2(a - d)$.

For values of $2ak\sqrt{p}$ greater than 5·3 the value of d to within 1 % is given by $1/[k\sqrt{(2p)}]$.

Taking the value of the permeability of copper as 1 c.g.s. electromagnetic unit, and of the resistivity of copper as 1 600 c.g.s. electromagnetic units, Fig. 4 shows the equivalent width, expressed as a percentage of the total width, for copper strips 0·2, 0·5, 1·0 and 2·0 cm. wide, over a range of frequencies from 0 to 50 kc./s.

Thus, in calculating the leakage inductance of a transformer at any given frequency, whilst that component of inductance due to flux through air-gaps (the " gap inductance ") remains constant, the width of leakage-flux paths through copper must be taken as some proportion of the total width, which depends upon the copper section and the frequency. Thus the " copper inductance " is a function of frequency. That is, the quantity L_2'' (see Section II) may be written

$$L_2'' = L_{2g} + L_{2c}(f)$$

where L_{2g} is the " gap inductance " and is constant, whilst

$L_{2c}(f)$ is the " copper inductance," which is a function of the frequency.

In the conventional calculation of the leakage reactance of a transformer, the assumption is made that all portions of flux paths except those portions actually considered in the calculation have a return path through iron, which is regarded as being of zero reluctance. This assumption would be quite valid if the iron were in very close proximity to the coils; but in practice the iron is at a definite distance from the copper, and to take account of this it is usual to correct the calculated reactance value by applying the Rogowski* correction factor (usually denoted by K), which decreases as the gap between core iron and coils is increased. For the single-phase transformer used by the authors this correction factor (which, of course, applies to power frequencies only) is $K = 0{\cdot}939$. For the same transformer coils, with the iron removed to infinity, K would become 0·931. It is then apparent that any increase in reluctance of flux paths through the iron, at high frequencies, could only reduce the effective transformer reactance by less than 1 %; thus any correction due to eddy currents in iron must be negligible.

The resultant calculation of the variation of effective inductance with frequency, for the single-phase transformer, is shown by the full line of Fig. 3, falling from its power-frequency value of 2 130 μH to a value of 1 680 μH at 50 kc./s. It will be seen that the calculated values agree reasonably well with the values obtained by experiment, the maximum discrepancy being about

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* See, for example, page 69 of Reference (4).

* See page 78 of Reference (4).

10 % at 50 kc./s. The experimental data appear to indicate that the effective inductance will still fall slightly for frequencies above 20 kc./s., whilst the calculation shows that at 20 kc./s. the inductance should become sensibly constant. This difference is possibly due to the feature that in the calculation no account has been taken of the fact that some of the leakage flux must for some part of its path pass through copper in an axial direction.

The width of the copper normal to this axial flux for this transformer is considerably less (of the order of 0·2 cm.) than the axial width of 1·0 cm., and it can be seen from Fig. 4, Curve (*a*), that for strips of this width the equivalent width (and hence the effective inductance) will decrease appreciably for frequencies above 20 kc./s.

In the present instance the ratio (copper thickness)/(insulation thickness) in the direction of the leakage flux was approximately 15 : 1. In transformers of the concentric type, such as those of the substation considered in Section V, where this ratio is considerably less, it is necessary to make allowance for the fact that the reduction in effective width only applies to a proportion of the flux path.

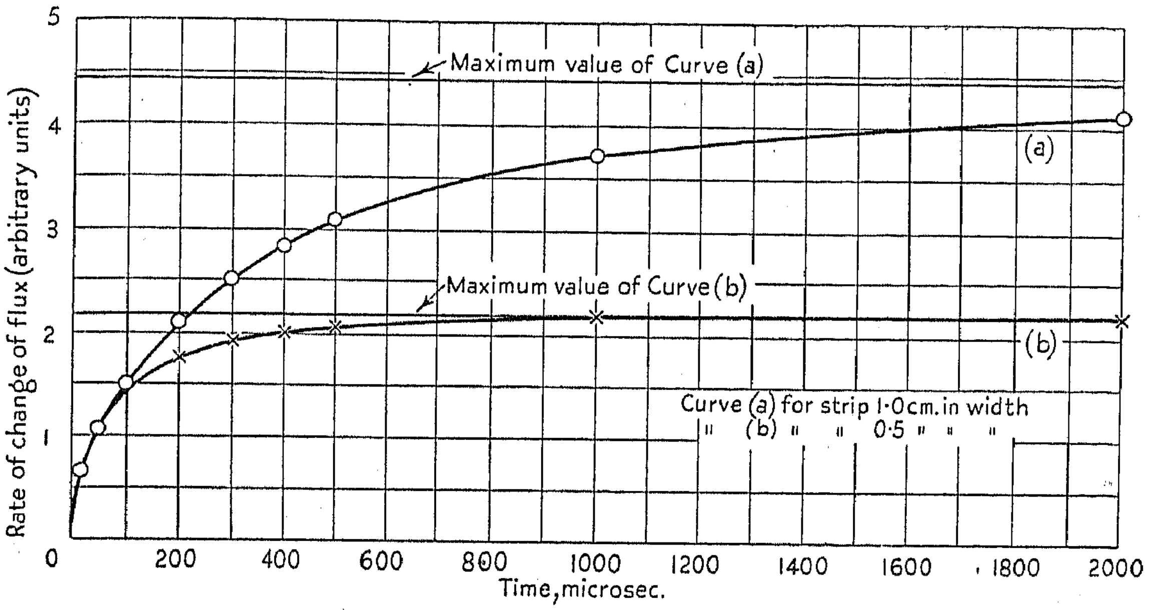

Fig. 5.—Theoretical curve showing variation with time of the rate of change of total flux through a copper strip in a magnetic field increasing linearly with time. [This variation is proportional to the variation of $L_{2c}(t)$.]

IV. VARIATION, WITH TIME, OF THE INDUCTANCE DETERMINING THE AMPLITUDE OF THE RESTRIKING-VOLTAGE TRANSIENT

A further result due to the presence of eddy currents in the copper windings is that (as is shown in Appendix II) on the application of a linearly increasing current the copper is effectively impermeable to leakage flux at zero time. This effective impermeability decreases with time, at a rate depending on the width of the copper, until the copper becomes effectively completely permeable.

Thus the inductance determining the amplitude of the restriking-voltage transient L_2' (see Section II) is at zero time equal to the "gap inductance," rising with time to the total inductance. That is,

$$L_2' = L_{2g} + L_{2c}(t)$$

where L_{2g} is the "gap inductance" and $L_{2c}(t)$ is the "copper inductance" expressed as a function of time.

The manner in which the variable portion $L_{2c}(t)$ may be calculated is shown in Appendix II, and a typical example of the function $L_{2c}(t)$ is shown plotted in Fig. 5.

Fig. 2 shows a replot of an R.V.I. record taken across the secondary winding with the mean of the envelope of oscillations extrapolated back to zero time. This mean line shows the function AL_2'. Comparison between calculated and observed laws for the function AL_2' can best be made by comparing the values of L_{2g} (the value at zero time) and of the half-value period.

It will be seen from Table 3 that the measured times, for the inductance, as represented by the mean of the envelope, to reach a value midway between the calculated inductance at zero time and the value at power frequency, agree closely with the theoretical time. Owing to the arbitrary nature of the extrapolation to zero time, however, the measured values of the inductance at zero time and of the times to reach the mean of the measured inductances are not in such good agreement with the calculated values.

V. SHORT-CIRCUIT TESTS IN MEDIUM-VOLTAGE SUBSTATION: SWITCH AND TEST CONNECTIONS

(a) Substation

Field short-circuit tests which showed to a marked extent the phenomena described above were made in a substation arranged as shown in Fig. 6. A normal high-voltage feeder to the substation was broken and brought to a special circuit-breaker, A, erected outside the substation and used as a master breaker. A circuit was taken thence through the normal feeder circuit-breaker to the substation h.v. busbars. Between these busbars and the normal l.v. busbars either one, two or three similar 1 500-kVA 6·6/0·425-kV transformers of 5 % reactance could be connected in parallel, using the normal switchgear. In the tests here reported one or two transformers only were used.

Two 0·4-sq. in. 3-core paper-insulated lead-sheathed cables in parallel, each $12\frac{3}{4}$ yd. long, were connected directly to the 425-V busbars, and were led to a 440-V

Table 3

DATA FROM R.V.I. RECORDS ON ISOLATED TRANSFORMER

1	2	3	4	5	6	7	8	9	10
External capacitance, μF	Resonant frequency, kc./s.	Inductance at zero time		Inductance at power frequency		Measured time to reach mean of —		Calculated time to reach mean of calculated inductance, μsec.	Inductance characteristic of frequency, μH
		Measured, μH	Calculated, μH	Measured, μH	Calculated, μH	Measured inductance, μsec.	Calculated inductance, μsec.		
0·005	43·5	1 610	1 680	2 100	2 130	170	230	225	1 490
0·008	37·2	1 630	1 680	2 100	2 130	190	230	225	1 530
0·012	31·6	1 710	1 680	2 100	2 130	230	240	225	1 580
0·019	26·2	1 730	1 680	2 100	2 130	230	220	225	1 610
0·030	21·4	1 750	1 680	2 100	2 130	240	220	225	1 630

circuit-breaker, B, erected outside the substation. The outgoing terminals of this circuit-breaker were connected together through current-measuring shunts, and earthed, the earth connection being led back to the busbars parallel to the cables. When this circuit-breaker was closed, there existed a 3-phase-earth fault on the 425-V busbars.

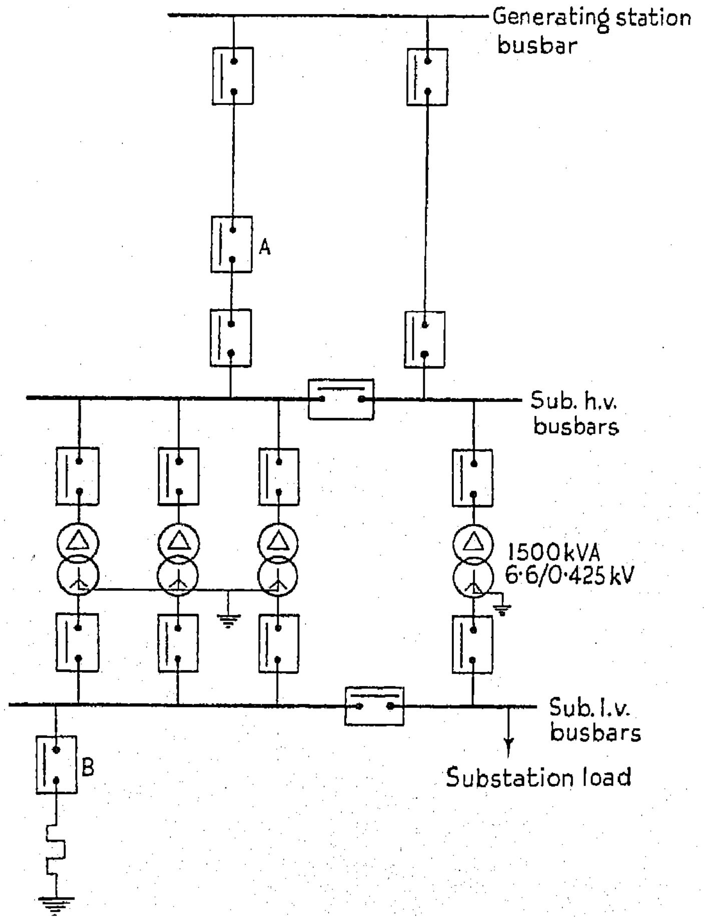

Fig. 6.—Arrangement of substation for tests.

(b) Test Switches

The master circuit-breaker A, on the high-voltage side, was a 33-kV circuit-breaker fitted with arc-control pots of the side-blast baffle type. This breaker had been previously used in similar tests[6] and had been shown to possess suitable characteristics for use as a β-switch* in recording restriking-voltage transients. The circuit-breaker B was a 440-V breaker specially fitted with side-blast baffle pots to make it as suitable as practicable for use in these experiments.

(c) Control and Recording Arrangements

Control and recording equipment were supplied from a test van. The method of control was as follows: The 440-V circuit-breaker B was closed by hand. All circuit-breakers in the substation through which fault current would pass were locked in. The 6·6-kV cable to the open master breaker A was switched on to the busbars at the generating station. Timed control from a rotating drum in the test van was used (i) to open oscillograph camera shutters; (ii) to close the master breaker A, thus throwing a fault on to the system; (iii) to open either breaker A or B as desired, clearing the fault from either the 6·6-kV or the 425-V side; (iv) to close oscillograph camera shutters; and (v) to open circuit-breaker A if this had not already opened in the test cycle adopted. The present paper deals only with those tests in which the fault was cleared from the 425-V side.

Duddell oscillograph vibrators were used to record (i) the fault current in the 425-V system (measured from the shunts at the fault point previously referred to) and (ii) the voltage across each phase of either breaker A or B, whichever was used to clear the fault. Voltage transformers were used on the 6·6-kV side, and resistance voltage-dividers on the 425-V side. In addition, cathode-ray oscillograms were taken of the voltage across each break of circuit-breaker B, and of the voltages to earth on the 6·6-kV system.

The recording circuits used are illustrated in Fig. 7.

VI. RECORDS OBTAINED

(a) Duddell Oscillograms

Fig. 8 (see Plate 1) is a typical Duddell oscillograph record obtained in these tests, showing fault current, arcing voltage and recovery voltage, for a fault supplied

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* See Section III of Reference (6).

Plate 1

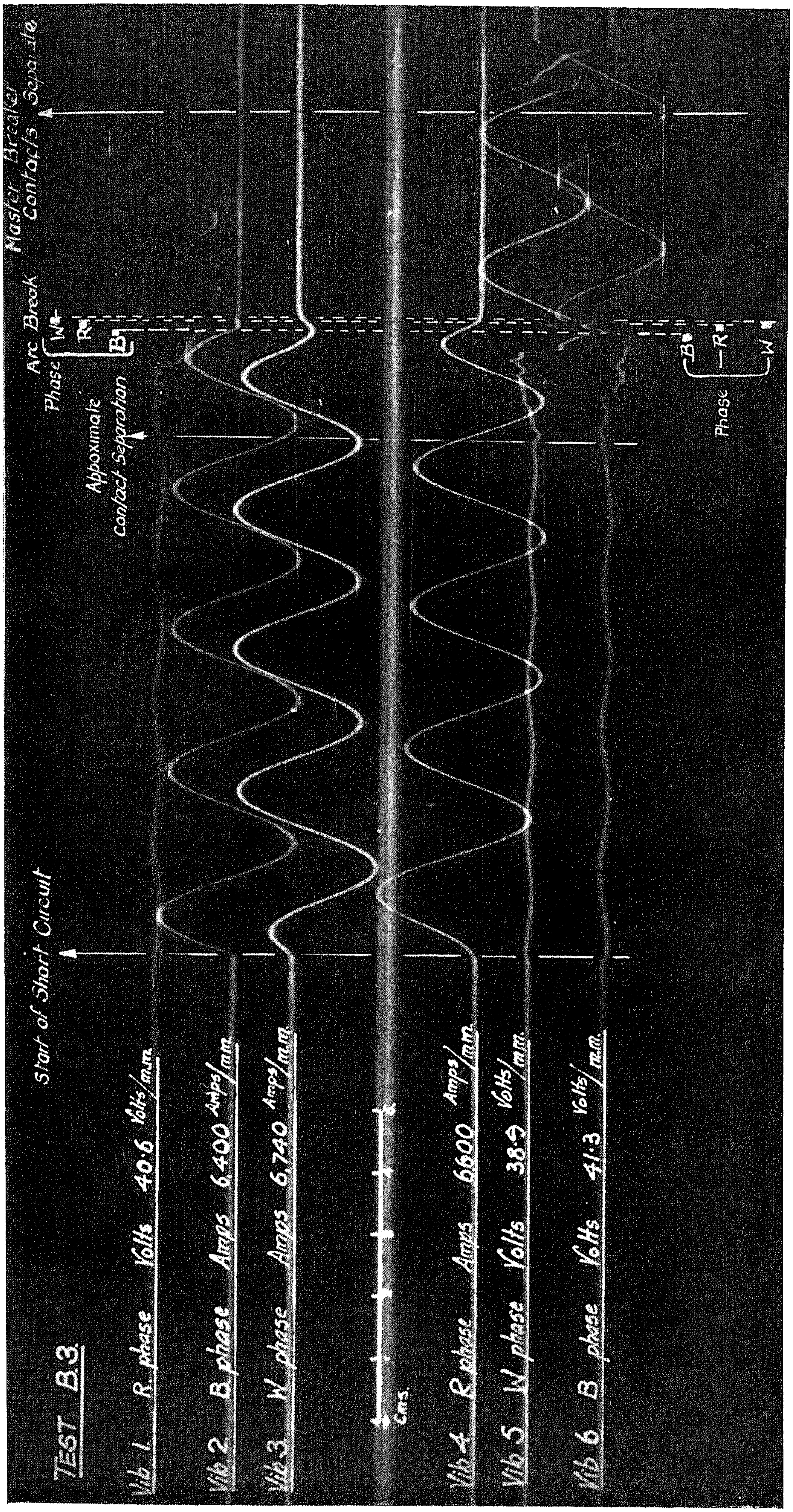


Fig. 8.—Duddell oscillograph record showing 3-phase-earth fault supplied by two transformers, cleared by circuit-breaker B (Fig. 6).

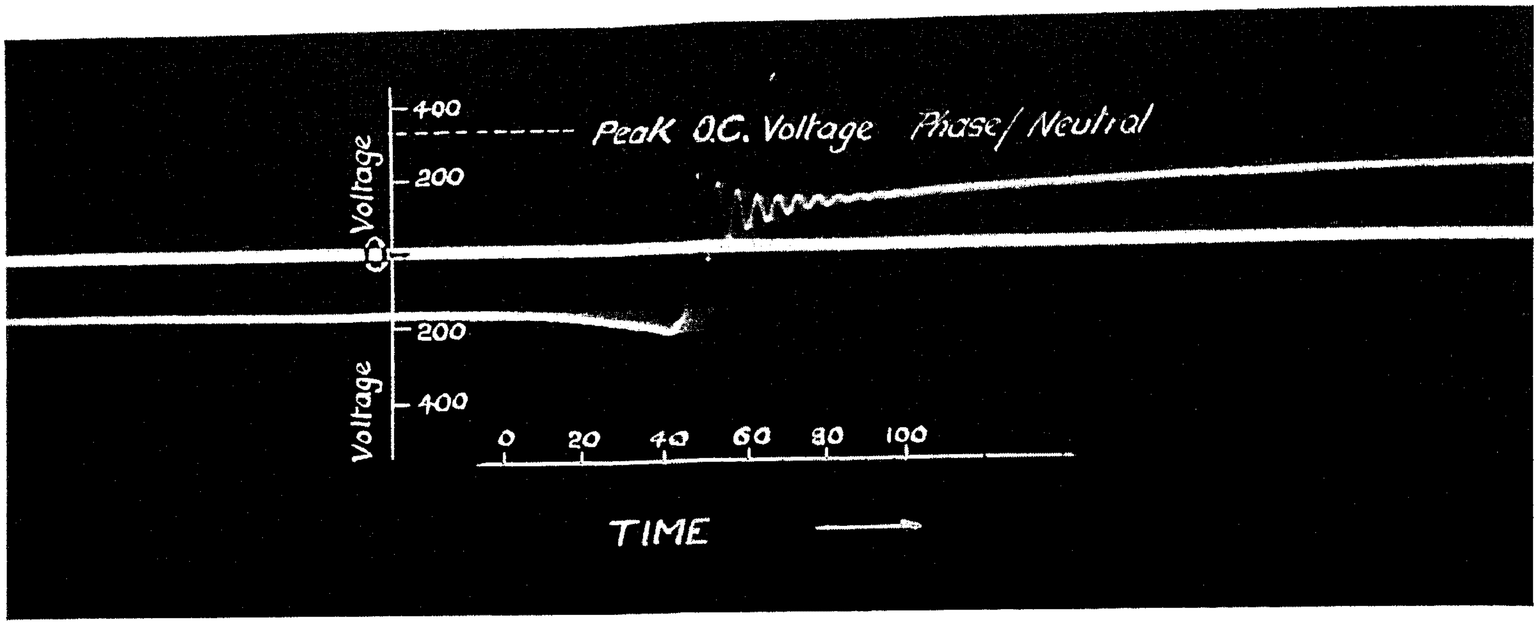
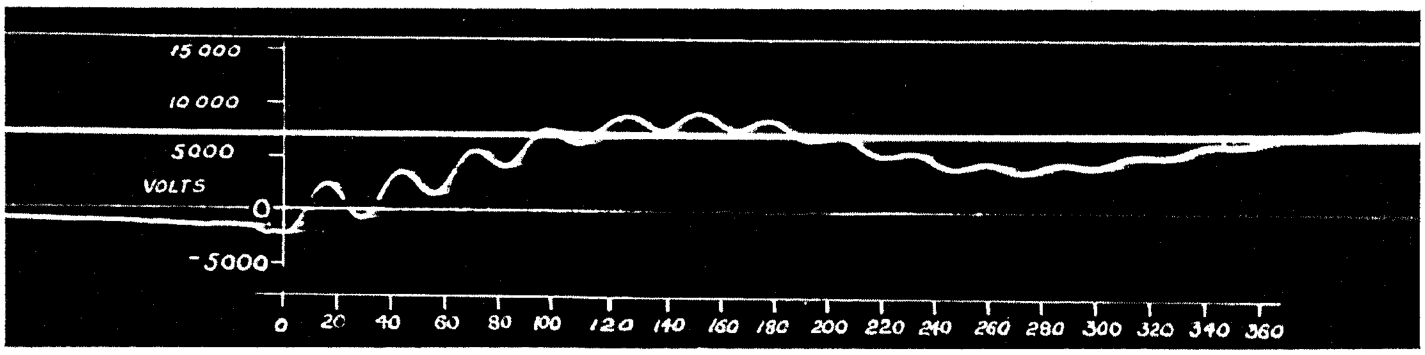


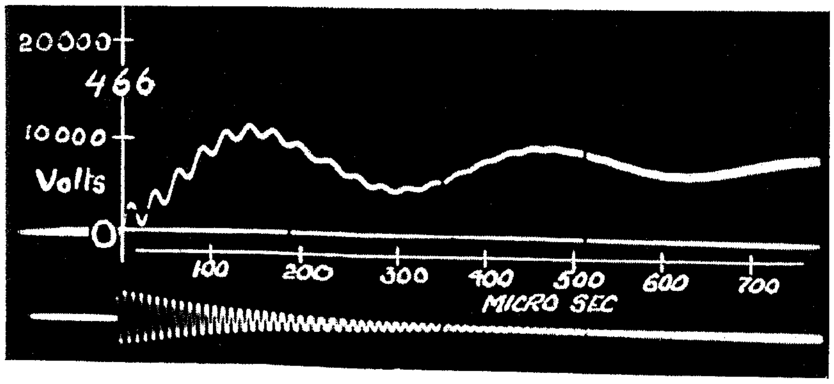
Fig. 9.—Cathode-ray oscillogram showing transient of restriking voltage at clearance of first phase of 3-phase-earth fault fed by one transformer.

(Time scale is in microseconds.)



Time, microsec.

(*a*)



100-kc./s. time wave.

(*b*)

Fig. 17.—Restriking-voltage transients of test circuit of Fig. 1(*a*) with 0·0133 μF (total) across the secondary winding.

(*a*) is recorded under short-circuit conditions by cathode-ray oscillograph.
(*b*) is recorded under no-load conditions by restriking-voltage indicator.
The frequency of the faster oscillating component is 35·3 kc./s.

by two transformers in parallel. It is of interest to note that in the white phase, the last to clear, the influence of the arc voltage has been so great that the restriking voltage is in the same sense as the arc voltage (owing to the current being forced down to zero prior to the time at which it would have reached its peak without arcing voltage). The oscillogram shown does not represent an isolated case of this phenomenon, which appeared in two of the three tests in this series.

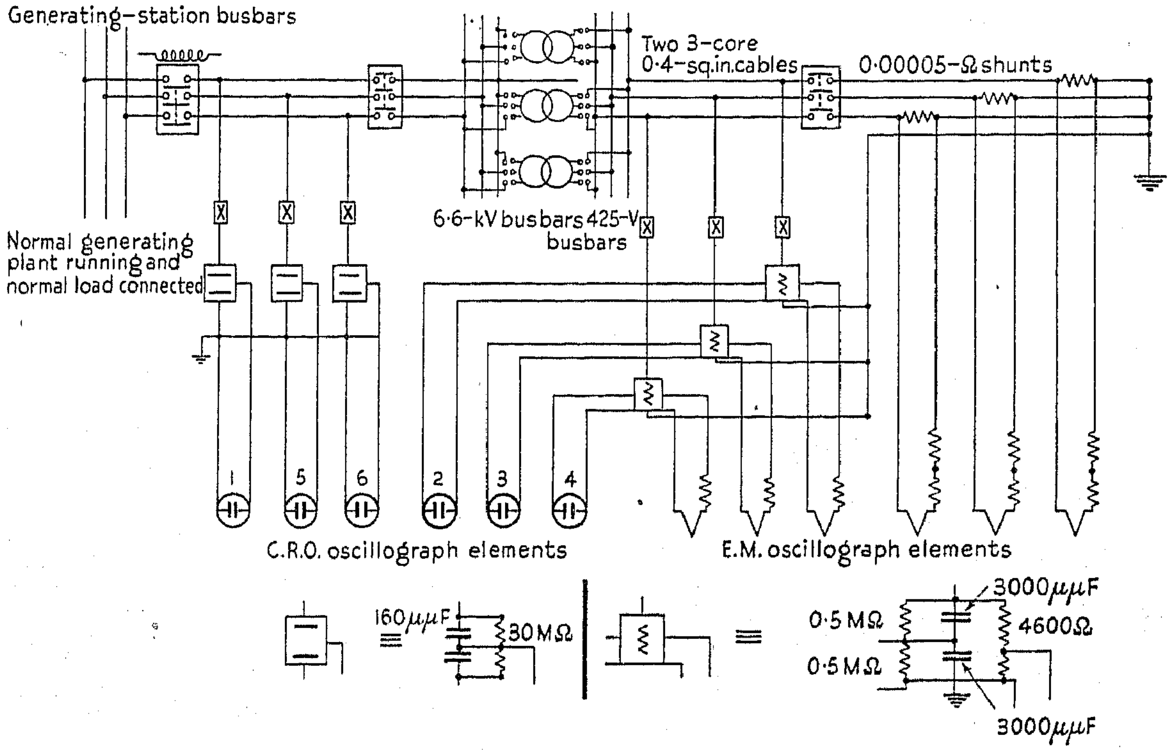

Generating-station busbars
Two 3-core 0·4-sq.in.cables
0·00005-Ω shunts
Normal generating plant running and normal load connected
6·6-kV busbars
425-V busbars
1
5
6
2
3
4
C.R.O. oscillograph elements
E.M. oscillograph elements
160μμF
30MΩ
0·5MΩ
0·5MΩ
3000μμF
4600Ω
3000μμF

Fig. 7.—Recording circuits.

(b) Cathode-Ray Oscillograms

Fig. 9 (see Plate 1) is a typical portion of a cathode-ray oscillogram obtained in these tests, showing the final arc voltage and the transient of restriking voltage at the clearance of the first phase of a 3-phase-earth fault supplied by one transformer.

VII. CIRCUIT PARAMETERS

(a) General

In the present instance, when the system under test is represented by an elementary diagram such as that of Fig. 1(*c*), it is found that the reactance L_1 is only about 10 % of the reactance L_2, and the frequency of the system L_1C_1 is very low compared with that of L_2C_2. As has been explained above, under these conditions the contribution of L_1C_1 to the transient of restriking voltage is very small indeed, and in what follows L_1C_1 is treated as a short-circuit so far as the transient of restriking voltage is concerned.

All the short-circuits involved in the present tests were short-circuits to earth; thus the zero phase-sequence impedance network of the system enters into the determination of the transient of restriking voltage at each stage of the clearance of the faults. Diagrams showing the method of interconnection of the separate phase-sequence impedance systems for the calculation of transients of restriking voltage at each stage of clearance have been published previously,[3] but the diagrams are here reproduced (Fig. 10) for ease of reference. Only two networks (positive and zero phase-sequence) appear in these diagrams, since the positive and negative phase-sequence networks may be regarded as identical so far as transients of restriking voltage are concerned.

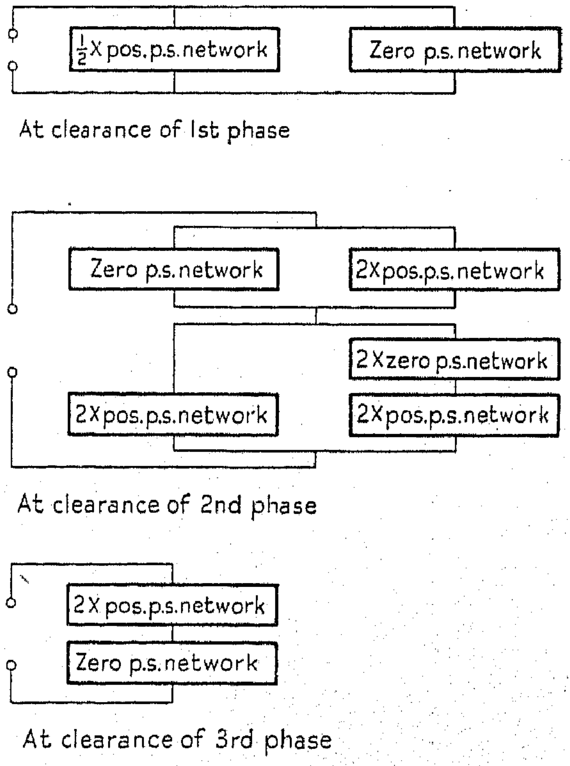


Fig. 10.—Combinations of positive and zero phase-sequence networks determining restriking and recovery voltages at clearance of successive stages at the interruption of a 3-phase-earth fault, where positive and negative phase-sequence impedance networks are identical.

For the system in question, the reactance of the transformer was calculated as a function of frequency and of time, as described in Sections (*a*) and (*b*) of Appendix III. The calculated values are shown in Fig. 11, which includes the reactance of the short length of cable from switch to transformers. The appropriate circuit capacitances, with the other circuit parameters, are shown in Fig. 12 [and see Appendix III (*c*)].

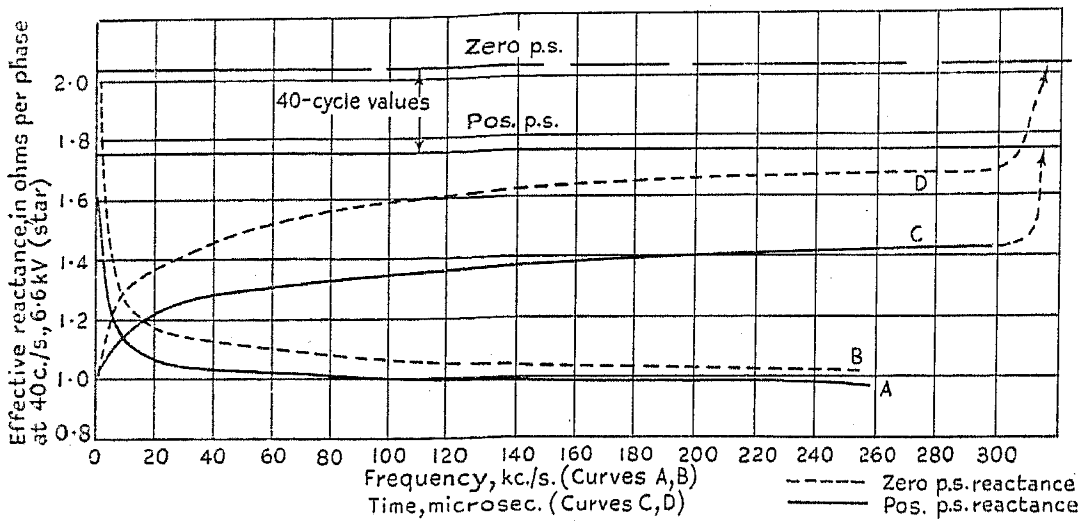


Fig. 11.—Variation of positive and zero phase-sequence reactance with frequency, for oscillatory applied phenomena, and with time, for linear applied current $i = At$.

Figures relate to one 1 500-kVA 5 % 6·6/0·425-kV transformer with cables to fault point. Cable reactance, 0·16 Ω per phase at 6·6 kV. Positive phase-sequence reactance, 0·16 Ω per phase at 6·6 kV.

(b) Circuit Oscillation Frequencies

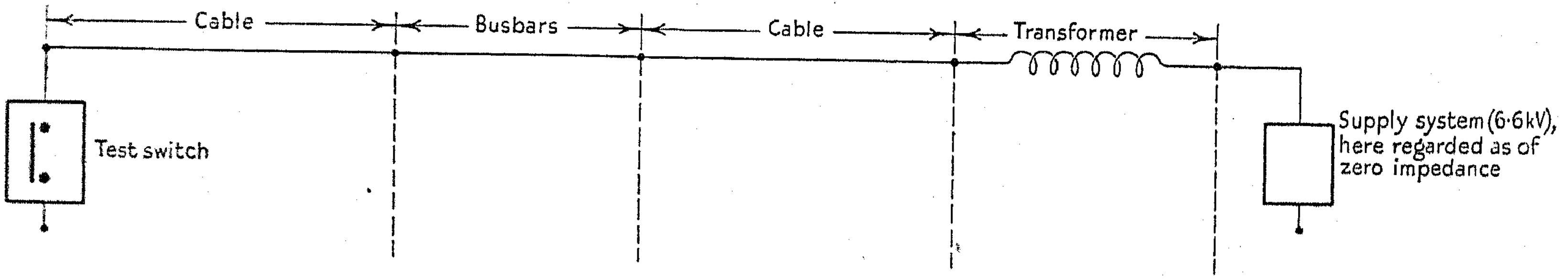
If the zero phase-sequence reactance and capacitance per phase (ωL_0 and C_0) are written as $m\omega L_2$, nC_2, where ωL_2 and C_2 are the positive phase-sequence reactance and capacitance per phase, it is possible, from consideration of the diagrams of Fig. 10, to express the various frequencies appearing in the transients of restriking voltage at the clearance of the various stages of a fault, in terms of m, n and f_1, where $f_1 = 1/[2\pi\sqrt{(L_2C_2)}]$. These frequencies for a 3-phase-earth fault are set out in Table 4, Cols. 1 and 2. In general, there will be more than one frequency associated with each stage of fault clearance. It is not usually possible to separate these out from records of restriking-voltage transients, unless they are markedly different. In the present instance the frequencies are very nearly equal and the apparent frequency should lie between the calculated frequencies.

VIII CALCULATED AND OBSERVED TRANSIENTS OF RESTRIKING VOLTAGE

(a) Frequencies

It is convenient to compare calculated and observed transients of restriking voltage under three heads: (*a*) frequency of damped sinusoidal oscillation, (*b*) the mean about which it is described, and (*c*) the decrement of the oscillation.

For the single transformer with cables up to the test



						Total	
Positive phase sequence	Capacitance	2·48 × 10−2*	0·95 × 10−2†	1·71 × 10−2*	0·2 × 10−2 ‡	5·34 × 10−2	μF per phase
	Reactance	0·16*	Negligible	Negligible	See Fig. 11	See Fig. 11	Ohms per phase§
Zero phase sequence	Capacitance	1·24 × 10−2*	0·95 × 10−2†	1·71 × 10−2*	0·2 × 10−2‡	4·1 × 10−2	μF per phase
	Reactance	←——0·6††——→			See Fig. 11	See Fig. 11	Ohms per phase§
Material		Two 12⅔-yd. runs in parallel, 0·4-sq. in. 3-core p.i.l.s. 600-V cable		3 runs in parallel per phase, each 4 yd. long. 0·75-sq. in. cambric-insulated lead-sheathed single-core cable			

ig. 12.—Details of circuit parameters concerned in transients of restriking voltage. (Busbars supplied through one transformer.)

* Calculated from cable dimensions.
† Estimated from measurements on similar busbars.
†† Estimated.
‡ Estimated from measurements on similar transformer.
§ Ohms per phase referred from 425 V to 6 600 V.

switch B (Fig. 6), the reactances and capacitances detailed in Fig. 12 apply. The reactance values appropriate to the true oscillatory frequencies may be obtained by successive approximations to the frequency, starting with the power-frequency reactance. Using these figures, the calculated frequencies are as shown in Table 4, Col. 4. As previously mentioned, it is not possible to pick out the individual frequencies at each stage of the interruption, but the observed frequencies should lie between the calculated frequencies for each stage. The means of these calculated frequencies are shown in Table 4, Col. 5, and their ratios in Col. 6.

The observed mean frequencies at each stage are shown in Col. 7, and their ratios in Col. 8. The agreement between the calculated and observed figures may be considered remarkably good, having regard to the manner in which the reactance and capacitance figures were obtained.

(b) The Mean of the Restriking-Voltage Transient

The " mean " of the restriking-voltage transient (i.e. the mean line about which the oscillatory component is described) should, for a constant reactance, consist of a Heaviside function of voltage proportional to the reactance and to the current interrupted, superposed on a voltage of the form $e = \beta t$, where β depends on the series resistance of the circuit and the current interrupted. In cases such as the present where the reactance is not a constant, the Heaviside unit function voltage is replaced by a voltage approximately proportional at every instant to the effective reactance at that instant.

The effective reactance at the clearance of the first phase of a 3-phase-earth short-circuit consists (see Fig. 10) of half the positive phase-sequence reactance in parallel with the zero phase-sequence reactance. Assuming that the total reactance of the parallel systems at any time is equal to the value given by considering the instantaneous reactances at that time in parallel, a curve of overall reactance against time can be constructed from the curves C, D of Fig. 11. This curve, with reactance ordinates transformed to voltage ordinates, and the resistive linear component (*b*) (Fig. 13) added, is shown in Fig. 13(*a*). This now represents the calculated mean line about which oscillations are described in the transient of restriking voltage at the clearance of the first phase of a 3-phase-earth fault on the system we are considering.

The observed transient of restriking voltage at the clearance of the first phase in a 3-phase-earth fault supplied by one transformer is shown in Fig. 13(*c*), the mean of oscillation being shown dotted. It will be seen that in form, though not in ordinate values, the observed curve agrees remarkably well with the calculated curve. True comparison, of course, is only possible between the calculated curve and the observed curve properly corrected to remove the effects of arc voltage, and this latter course presents considerable difficulty, in view of the magnitude of the final arc voltage and of the fact that throughout the last half-cycle the arc voltage has persisted large. However, in a system such as that under consideration, where the reactance behind the last plant unit may be regarded as negligible, no assumed form of arc voltage in a system where L_2 [see Fig. 1(*c*)] is a constant, can give rise to a transient of restriking voltage of the form represented by Curve (*c*) in Fig. 13, and with any assumed arc voltage the actual swing of the restriking-voltage transient, starting at the final arc-voltage peak, is directly proportional to the rate of

Table 4

CALCULATED AND OBSERVED FREQUENCIES IN THE TRANSIENTS OF RESTRIKING VOLTAGE AT THE SUCCESSIVE STAGES IN THE CLEARANCE OF A 3-PHASE-EARTH FAULT BY CIRCUIT-BREAKER B (FIG. 6): FAULT FED BY ONE TRANSFORMER

1	2	3	4	5	6	7	8
Stage of clearance	Frequencies (kc./s.)	Frequencies (kc./s.) for $m = 1{\cdot}07$, $n = 0{\cdot}78$	Frequencies (kc./s.) for $f_1 = 174$	Average of Col. 4 for each stage	Ratio of calculated frequencies to lowest calculated frequency	Observed frequencies (kc./s.)	Ratio of observed frequencies to lowest observed frequency
First phase	$f_1 \times \sqrt{\dfrac{1+2m}{m(2+n)}}$	$1{\cdot}025 f_1$	178	178	1·02	187	1·02
Second phase	f_1	f_1	174	174	1·00	184	1·00
	$f_1 \times \sqrt{\dfrac{m(3+n)}{3+m}}$	$0{\cdot}99 f_1$	172				
	$f_1 \times \sqrt{\dfrac{2+n}{m(1+2n)}}$	$1{\cdot}01 f_1$	177				
Third phase	f_1	f_1	174	182	1·05	198	1·08
	$f_1 \times \sqrt{(1/mn)}$	$1{\cdot}095 f_1$	191				

change of current in the arc at the instant the current reaches zero. That is, the form of the transient of restriking voltage is independent of the arc voltage, only its amplitude varying. Since there is, however, no reasonable means of finding out what was the rate of change of arc current at the time of reaching zero, a logical manner of comparing the observed and calculated transients appears to be to express both in terms of percentages of their value at some given instant. This is done in Fig. 13, Curves (*d*) and (*e*), and it will be seen that the agreement is reasonably good.

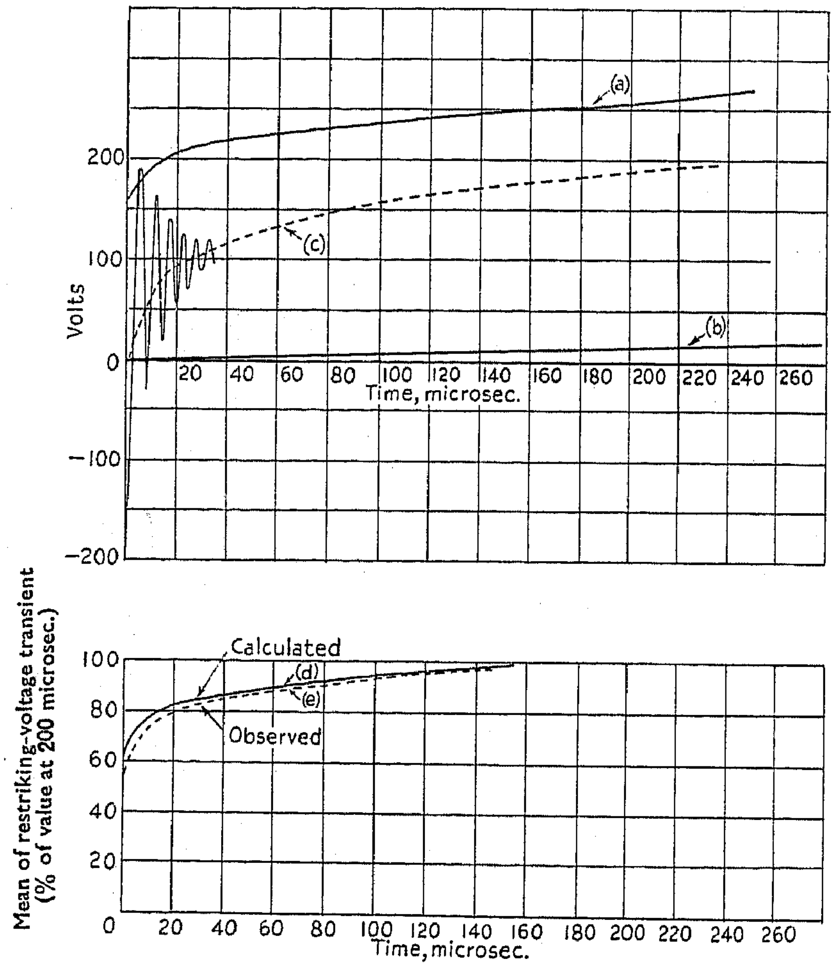


Fig. 13.—Mean transient of restriking voltage at clearance of first phase. (Fault fed through one transformer.)

Fig. 14 shows the result of carrying out, for the third phase to clear, the process described above for the first phase. Curve (*a*) is the calculated inherent transient of restriking voltage made up of the sum of the reactance terms from Fig. 11, together with a resistance term [shown separately in Curve (*b*)]. Curve (*c*) is the mean of the observed restriking-voltage transient. Curves (*d*) and (*e*) are respectively the calculated and observed transients of restriking voltage, plotted in each case in terms of the voltage at any instant as a percentage of the total change in voltage over 200 microsec. from the current zero, which is assumed to coincide with the final peak arc voltage in Curve (*c*). Here again the agreement is reasonably good, having regard especially to the enormous influence of arc voltage in Curve (*c*), which does not cross the zero line to reach the normal polarity of recovery voltage until nearly $\frac{1}{4}$ cycle after the current zero.

It will be seen from Fig. 10 that the calculation of the transient of restriking voltage for the second phase to clear would be a fairly lengthy business, and it has not been attempted. There is, however, no reason to suppose that the transient would be much different in character from those at the clearance of the 1st and 3rd phases.

(c) Decrements

In each of the transients of restriking voltage recorded, the decay coefficient (after all effects of post-arc conductivity had vanished) of the decrement term of the transient was of the order of 10^5 (i.e. the half-value period was of the order of 7 microsec.). The effective shunt damping resistance necessary to give such a decay coefficient is of the order of 100 ohms per phase. It has not yet been found possible to associate this quantity with any of the circuit parameters. It is interesting to note that this resistance per phase is of the order of 3 times the shunt resistance per phase equivalent to the transformer iron loss.[*] It is, however, extremely probable that the damping in the circuit is mainly associated with the eddy-current losses in the transformer copper, and is thus in fact unrelated to the iron losses.

The present results agree with all previous observations made on transients of restriking voltage in relation to transformers, in that the degree of damping existing is not such as to reduce the inherent rate of rise of voltage by more than about 10 % below the value calculated on the assumption that damping may be neglected.

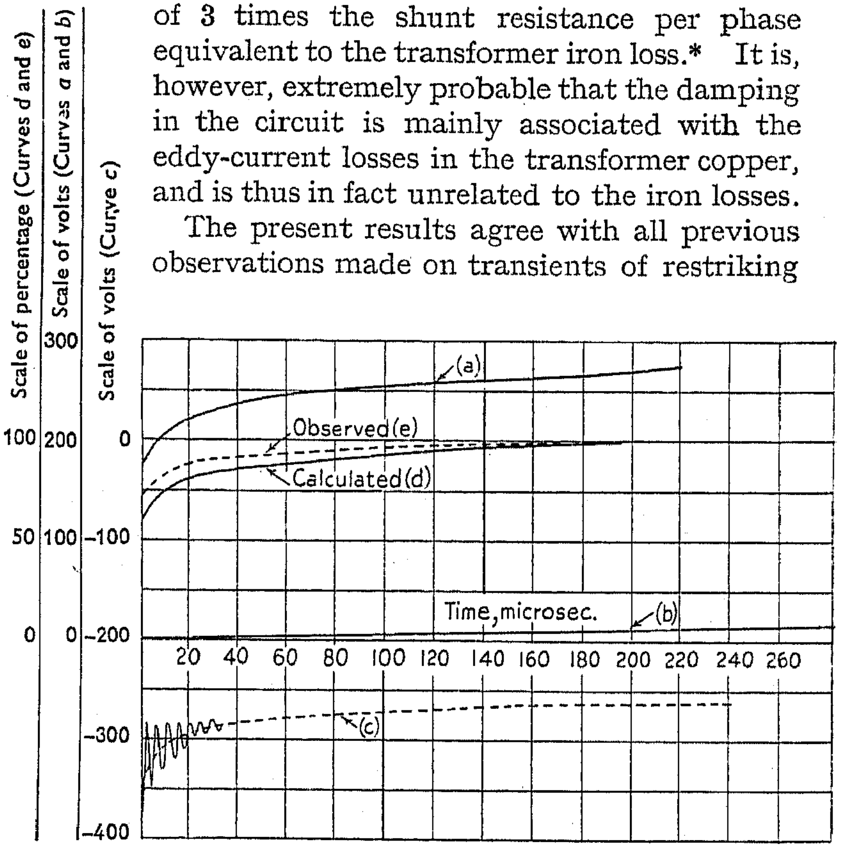


Fig. 14.—Mean transient of restriking voltage at clearance of third phase. (Fault fed from one transformer.)

Curve (*c*) starts at — 600 volts.

(d) Results with Two Transformers Supplying Busbars

One test only was made with Switch B (Fig. 6) clearing a fault supplied by two transformers in parallel, and in this test only one of the transients of restriking voltage recorded was sufficiently unmodified by post-arc resistance in the arc gap to enable the results to be analysed as in the case of the tests with one transformer treated above. The transient unaffected by these phenomena was that at the clearance of the third phase. In this test, the observed frequency of the restriking-voltage transient was 248 kc./s.: the frequency calculated on the basis of the variable transformer reactance was 190 kc./s. Comparison between the calculated mean transient of restriking voltage and the observed transient is shown in Fig. 15. Here, as in other cases examined, the agreement appears to be reasonably good.

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[*] Cf. Reference (1), in which, in tests on a 66/33-kV transformer, the effective shunt resistance per phase necessary to account for damping was stated to be half the resistance equivalent to the transformer iron loss.

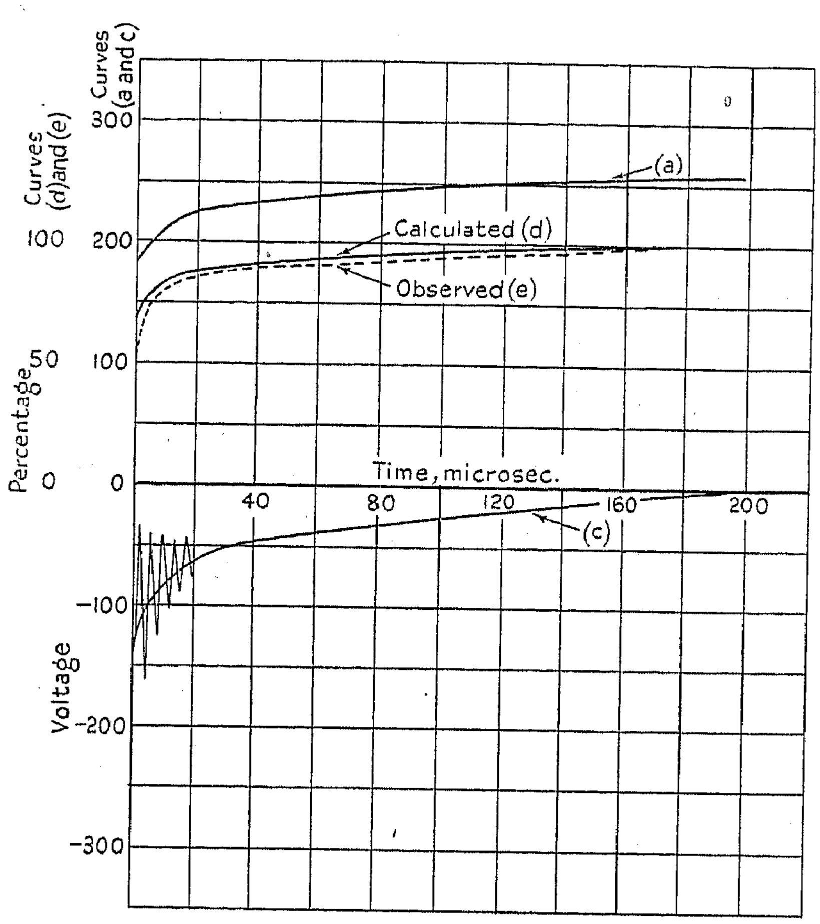

Fig. 15.—Mean transient of restriking voltage at clearance of third phase. (Fault fed from two transformers in parallel.)

Curve (*c*) starts at — 450 volts.

IX. PRACTICAL EFFECT OF EDDY CURRENTS IN TRANSFORMER WINDINGS ON RESTRIKING-VOLTAGE TRANSIENTS FOR A CIRCUIT-BREAKER UNDER SERVICE CONDITIONS

It is instructive to compare the transient of restriking voltage for a given circuit-breaker under service conditions, calculated on the basis of power-frequency parameters, with the true transient of restriking voltage (i.e. with that calculated taking account of the considerations set out above).

Consider any circuit-breaker on the 425-V busbars of Fig. 6, clearing a phase-phase fault on its outgoing feeder near the circuit-breaker terminals, when the supply to the busbar is through a single transformer. In calculating the transient of restriking voltage from power-frequency parameters, the only difficulty arises in estimating the resistance R in a network such as that represented by Fig. 1(*c*). A lower limit for this resistance would be zero: an upper limit one might justifiably take would be a resistance of sufficient value to account for the iron losses in the transformer. Transients of restriking voltage calculated on the above basis, taking R equal to zero and equivalent to the iron-loss resistance respectively, are shown in Fig. 16, Curves A and B. In calculating transients of restriking voltage on this basis there would be a very strong bias in favour of the assumption that $R = 0$, since previous work has shown that there is usually very little damping of the oscillatory component of transients of restriking voltage associated with the reactance voltage of transformers.

Calculation of the transient of restriking voltage taking account of eddy currents in the transformer windings proceeds along the lines indicated in Section VIII, the only differences being that since the transient under consideration is that at the clearance of a phase-phase short-circuit, the positive-sequence network only is considered; also the capacitance and reactance of the cable from busbars to switch are now both zero. We are here justified in taking the value of R as that deduced from the experimental results. This transient is shown in Fig. 16, Curve C. The latter curve gives a rate of rise of voltage of about 280 volts per microsec., with a peak restriking voltage of 470 volts (78 % of system phase-phase peak volts), the calculated frequency being 250 kc./s.; whereas the transient calculated from power-frequency parameters, neglecting damping (Curve A), gives a rate of rise of voltage of 420 volts per microsec., with a peak restriking voltage of 1 000 volts (165 % of system phase-phase peak volts), the calculated frequency being 180 kc./s.

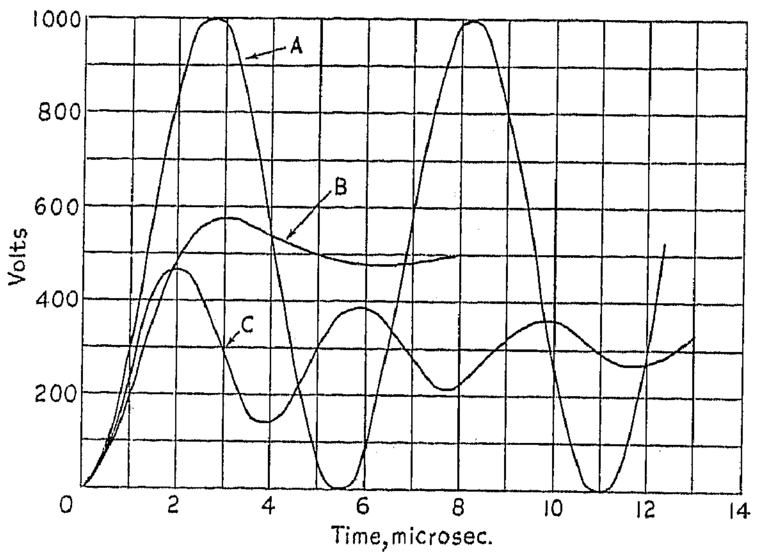

Fig. 16.—Calculated inherent transient of restriking voltage, circuit-breaker on substation busbars clearing a phase-phase fault fed by two transformers.

A. Calculated on basis of power-frequency parameters, neglecting damping.
B. Calculated on basis of power-frequency parameters, making very optimistic assumptions regarding damping.
C. Calculated on basis of theory justified by Figs. 14–15.

Transformer eddy-current phenomena are therefore responsible for reducing the rate of rise of voltage to about 70 %, and the peak restriking voltage to about 50 %, of the values which would exist in their absence (e.g. if transformers were wound with fine stranded wire).

X. NOTE ON THE REPRODUCTION OF SERVICE CONDITIONS IN TESTING

The reproduction for test purposes of the type of transient of restriking voltage here shown to be typical for medium-voltage busbars fed from step-down transformers, may present some difficulty. In general, the test voltage will be obtained by the use of step-down transformers fed from large 6·6-kV or 11-kV alternators, and these transformers will be of very low reactance compared with the reactance of the transformers supplying the circuit-breakers or busbars in service. If limitation of the fault current to the test value is obtained by the insertion of reactance in the supply to the transformers, the transient of restriking voltage will, in general, be of considerably lower frequency than the service transient, but will rise to a considerably higher peak value. If, on the other hand, reactance is inserted in the low-voltage supply from the transformers, the transient of restriking voltage will be of the same order of frequency as the service transient, but will rise to a considerably higher peak value. It is probable that the best approximation to the service transient will be obtained by inserting reactance in the low-voltage supply, and shunting a portion of the reactance with a suitable resistor.

It is to be noted that the difference between the restriking-voltage transient conditions on two busbars identical except that the transformers supplying them have the same reactance made up of different proportions of leakage flux through copper and through air, will be of the same type as between two circuits of constant parameters but with different phase-angles. Careful adjustment of the phase angle of a test circuit to match service conditions may therefore lead to erroneous results unless the further considerations here detailed are taken into account. In general, the higher the proportion of the total leakage flux which passes through conductors (iron or copper), the lower will be the first peak, and initial mean value, of restriking voltage (i.e. the lower will be the effective phase angle of an equivalent simple circuit).

XI. ACKNOWLEDGMENTS

The Electrical Research Association is indebted to the British Short-Circuit Testing Station, Ltd., by whom the short-circuit tests here described were arranged; and to Messrs. A. Reyrolle and Co., Ltd., who loaned the special circuit-breakers used in the tests. The Association is also indebted to Messrs. R. F. H. Brierly and W. W. Martin, of the above firms, for their organization of, and co-operation in, the tests.

The work here described forms part of the investigations into the phenomena of arc rupture being carried out on behalf of the E.R.A. by Dr. W. B. Whitney.

XII. CONCLUSIONS

1. The leakage inductance of a transformer, in so far as it determines the frequency and amplitude of a restriking-voltage transient, is a parameter which varies with frequency and with time, owing to the screening effects of eddy currents in the windings.

2. In investigating these variations it is necessary to regard the leakage inductance as composed of two components: one component is due to the contribution of the leakage flux through the air-gaps between the windings (the " gap inductance "), and the other to the flux through the copper of the windings (the " copper inductance "). The latter may represent anything up to 50 % of the total.

3. The contribution to the leakage inductance of the windings, of the leakage flux through the iron core, is negligible and hence the screening effect of eddy currents in the iron cannot appreciably reduce the effective inductance at high frequencies.

4. In the determination of transients of restriking voltage the " gap inductance " is a constant and equal to its power-frequency value. The value of the " copper inductance " governing the amplitude is zero at zero time, rising to its power-frequency value with increase of time, while that governing the frequency is equal to its power-frequency value at power frequency and falls to zero value with increase of frequency.

5. The laws governing these variations may be calculated for any transformer in the manner described in the paper, and it is shown that the theory put forward agrees tolerably well with experimental results.

6. As a result of the above, inherent rates of rise of restriking voltage, and the first peaks of restriking voltage, may be in extreme cases as little as 70 % and 50 % of the values calculated from power-frequency parameters.

7. The resonant frequencies and effective inductances of a single-phase transformer for various values of shunt capacitance associated with the transients of restriking voltage under short-circuit conditions, are substantially the same as those determined under no-load conditions.

8. In the 6·6/12-kV transformer examined, the effective inductance fell to 80 % of its power-frequency value at 5 kc./s., and to 70 % at 50 kc./s. In the 6·6/0·425-kV transformer, corresponding figures for positive phase-sequence quantities were 69 % at 5 kc./s. and 55 % at 50 kc./s.

9. For cases where the supply is from 3-phase transformer units, and the fault under consideration is between one or more phases and earth, consideration must be given to the effect of similar eddy currents in the exciting-flux path for zero phase-sequence currents. Whilst this question has not been studied in detail, the theory underlying the approximate method of calculation used in this connection in the present paper appears to be sound and to yield reasonable results.

10. Differences between restriking-voltage conditions associated with the same transformers of the same reactance but different design, are of the same type as the differences between networks of different phase angle. Careful adjustment of phase angle in testing circuits, to match service conditions, will therefore give incomplete reproduction of what may almost be regarded as power-frequency recovery-voltage conditions, unless the considerations dealt with in this paper are taken into account.

11. Of two transformers otherwise identical, that one will show the greatest reduction in effective inductance, and consequently in rate of rise of voltage, in which the total copper section is least sub-divided. It follows that from the point of view of lowering the circuit severity in respect to circuit-breakers it is advantageous to sub-divide the windings of transformers as little as possible, subject to the other dictates of design, e.g. cost, efficiency, etc.: and conversely, in designing transformers for a circuit-breaker test plant in which maximum circuit severity is required, it is advantageous to sub-divide the windings to as great a degree as is compatible with the requirements of mechanical rigidity.

12. The work described may have some application in connection with "ripple control" and also with the transfer of harmonics through transformers.

13. The phenomena described are likely to be of greater importance for lower-voltage than for higher-voltage transformers.

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APPENDIX I

Experiment on Effective Inductance of a Transformer

Data on the effective inductance of the transformer under test were obtained in several ways. First a circuit such as that shown in Fig. 1(*a*), supplied from a 6 600-V 10 000-kVA alternator, was so arranged that the resonant frequency of the system L_1C_1 was always low compared with that of the system L_2C_2 over the range of values of C_2 used. Cathode-ray oscillograms obtained of the transients of restriking voltage across a suitable circuit-breaker having low final arc voltage and negligible post-arc conductivity were of the form shown in Fig. 17(*a*), Plate 2. The higher-frequency component of such a transient is of frequency very close to $1/[2\pi\sqrt{(L_2C_2)}]$, where L_2 is the appropriate value of the inductance and C_2 the total shunt capacitance, i.e. the external capacitance plus the self-capacitance of the transformer windings; and examination of the variation of frequency with varying capacitances yields information on effective inductance. Information gained from these records, which were obtained with a range of values of C_2 giving a wide range of frequencies, is particularly valuable since the test condition is actually the working condition to which the problem is related. Figures showing observed frequencies for different external capacitances are shown in Table 1, Col. 2.

Records similar in form to the above, and in the same manner capable of yielding information concerning effective inductance, were obtained by applying the restriking-voltage indicator[7] to the system of Fig. 1 when dead. A typical restriking-voltage transient so obtained is shown in Fig. 17(*b*), Plate 2, and the frequencies obtained for various values of total added capacitance measured from such records are given in Table 1, Col. 3.

R.V.I. records were also obtained with the transformer isolated and the primary winding short-circuited and earthed and the added capacitance placed directly across the secondary winding, to the terminals of which the instrument was applied. The frequencies observed for different capacitance values appear in Table 3, Col. 2.

The resonant frequency of the transformer (with primary short-circuited and earthed) with various values of external capacitance, may be measured by several methods involving the use of a variable-frequency oscillator.[8] Interpolated values of the measured frequency, appropriate to the external capacitances of Table 1, Col. 1, are shown in Table 1, Col. 4. It will be seen that these, which agree closely with the measured values in Cols. 2 and 3, are somewhat higher than the values shown in Table 1, Col. 5, which were calculated using the power-frequency inductance.

The methods described above, which necessitate the inclusion of the transformer within a resonant system, are all mainly suitable for frequencies above the audio range. At lower frequencies bridge measurements are more convenient, and such were made at 50 c./s. and 1 000 c./s. Suitable supplies for the measurement of the transformer reactance under full-load current in the usual manner were not available, but it was possible to calculate the reactance (and equivalent inductance) at 50 c./s. under short-circuit conditions from a study of a series of Duddell oscillograms of transformer primary voltage and secondary current. In addition, the final sustained amplitude of the R.V.I. records taken on the isolated transformer gives a direct measure of the power-frequency inductance. Values for the effective inductance obtained by these various methods are given in Table 2, together with the value obtained by direct calculation of the reactance at 50 c./s. by a normal design method. It will be seen that the 50-c./s. values agree very closely, whilst the 1 000-c./s. value is considerably lower. It is worth noting in passing that the oscillograms referred to above did not appear to indicate any cyclical variation of transformer reactance.

Before the data obtained at frequencies above 1 000 c./s. can be analysed to obtain values of effective inductance, it is necessary to determine the self-capacitance of the transformer. This can be obtained by normal methods, using a range of frequencies sufficiently narrow to avoid the pitfalls due to variation of inductance and to errors at the higher frequencies due to the increasing importance of the capacitance of taps on the windings.

The values of the leakage inductance obtained from the above data, for frequencies from 50 c./s. to 50 kc./s., are plotted in Fig. 3 to a base of frequency, an indication being given of the manner in which each point is obtained.

APPENDIX II

Variation, with Time, of the Total Flux through a Copper Strip in a Magnetic Field increasing Linearly with Time

Owing to the screening effect of eddy currents induced in a conducting plate by a varying magnetic field perpendicular to its surface, the intensity of the field will have different values at different distances from the sides of the plate. If hysteresis is neglected and the permeability assumed to be constant, the differential equation expressing the variation of the field H with time t and with the distance x from the centre of the plate is

$$\frac{\partial^2 H}{\partial x^2} = \frac{4\pi\mu}{\rho}\frac{\partial H}{\partial t}$$

where μ is the permeability and ρ the resistivity of the material of the plate.

For a field induced by a linearly increasing current and having a value $H_0 t$ at the surfaces of a plate of width $2a$, the solution of the above equation is

$$H = H_0 t \frac{\cosh \lambda x/\sqrt{t}}{\cosh \lambda a/\sqrt{t}}$$

where $\lambda = \sqrt{2}\sqrt{(2\pi\mu/\rho)}$.

For a linearly increasing current the inductance is proportional to a voltage expressed as the rate of change of this flux with time, and is given by

$$(\mu H_0/\lambda)\left[3t^{\frac{1}{2}} \tanh (a\lambda t^{-\frac{1}{2}}) - a\lambda \operatorname{sech}^2 (a\lambda t^{-\frac{1}{2}})\right]$$

reaching a maximum value of $2a\mu H_0$.

For values of $a\lambda t^{-\frac{1}{2}} > 3\cdot 0$, the expression reduces to $(\mu H_0/\lambda) 3t^{\frac{1}{2}}$.

APPENDIX III

The Reactances and Capacitances of the 3-Phase Transformer Unit and of the Transformer and Cables to the Fault Point

(a) The reactances of the transformer unit.

(i) *Positive phase-sequence reactance per phase.*—The reactance of the transformer at power frequency, calculated in the normal manner from the transformer dimensions, was 8 % lower than the value obtained by the makers on test. The power-frequency reactance corresponding to the effective inductance at various frequencies, and the effective power-frequency reactance as a function of time on the application of a linear current function, have been calculated in the manner described above by taking account of eddy-current phenomena, these reactance values, including the positive phase-sequence cable reactance, are shown in Curves A and C, Fig. 11.

It will be noted that all these calculations are based on data which, at power frequency, gave a calculated reactance 8 % lower than the measured reactance: to this extent, therefore, all the calculated values are probably lower than the values under the conditions postulated. Since, however, in the example treated above, on which careful measurements under laboratory conditions were made, it was found that at frequencies above, say, 10 kc./s. the measured effective reactances were in general lower than the calculated values (for a case where measurement at power frequency agreed with calculation), it is probable that the curves of Fig. 11 do in fact represent true values within ± 10 % throughout the range of frequencies and times covered.

(ii) *Zero phase-sequence reactance.*—The zero phase-sequence leakage reactance of a transformer is normally taken as being equal to the positive phase-sequence leakage reactance.

It is, however, strictly necessary to regard the exciting reactance of the transformer as being in parallel with the leakage reactance. In many cases this can be neglected since the exciting reactance is large, but in the special case of the zero phase-sequence reactance of 3-phase transformer units, the zero phase-sequence exciting reactance becomes comparable with the leakage reactance, and must be taken into account. It has not yet been found possible to develop accurate methods of calculating the zero phase-sequence impedance of 3-phase transformer units, since much of the flux concerned traverses stray paths through the transformer tank, etc. Stigant,[9] however, gives figures which show that for small transformers (100 kVA) the exciting impedance to zero phase-sequence voltages, sufficiently large to saturate the stray paths through iron, may (at power frequency) be of the order of 8 times the positive phase-sequence leakage reactance. Thus the effective zero phase-sequence reactance per phase of a 3-phase transformer unit, to power-frequency phenomena applied, will be of the order of 0·9 times the positive phase-sequence leakage reactance.

The eddy-current phenomena described above as affecting the positive phase-sequence leakage reactance under transient conditions, must also affect the zero phase-sequence exciting reactance. Since the bulk of the flux here concerned will pass through the core, it is possible to calculate the initial inductance at zero time as the leakage inductance between the winding concerned and a hypothetical thin winding at the core surface, making, if necessary, some correction for the impermeability (at zero time) of the copper of the winding other than that to which the phenomenon we are considering is applied (see Fig. 18). In the present instance the zero phase-sequence exciting reactance per phase at zero time, calculated on this basis, was 0·6 ohm. Taking the final value of zero phase-sequence exciting reactance per phase as 8 times the leakage reactance (see above), it may be assumed that the difference is due to the flux which passes through the iron core. Assuming a value of 2 500 c.g.s. electromagnetic units for the permeability of iron, and knowing the resistivity (10^4 c.g.s. e.m. units) and plate thickness, it is possible to calculate the flux through the iron at any time, as a percentage of the final flux. On these lines the curves of Fig. 19 have been constructed, representing the zero phase-sequence exciting reactance on the application of linear current. Fig. 20 similarly represents the zero phase-sequence exciting reactance as a function of frequency.

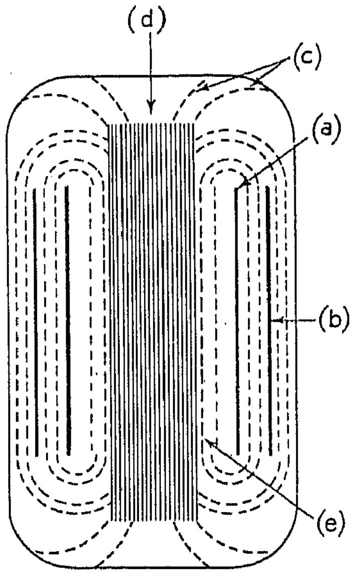

Fig. 18.—Zero phase-sequence exciting reactance of 3-phase transformer unit.

- (*a*) Secondary winding (to which phenomena are applied).
- (*b*) Primary winding.
- (*c*) Flux paths (power-frequency conditions).
- (*d*) Core.
- (*e*) Hypothetical thin winding at core, leakage reactance between (*a*) and (*e*) determining zero phase-sequence exciting admittance at zero time, when core is impermeable.

Note that (*b*) must also be considered to be impermeable at zero time.

The overall zero phase-sequence impedance is that represented by the leakage reactance in parallel with the exciting reactance. Making the assumption (which is not strictly correct but which is sufficiently accurate for our present purposes) that the overall impedance as a function of time can be obtained by taking values at each instant of each reactance and calculating a value for the two in parallel, we obtain for the overall zero phase-sequence reactance, including the cable reactance, as a function of time, the law shown as Curve D, Fig. 11.

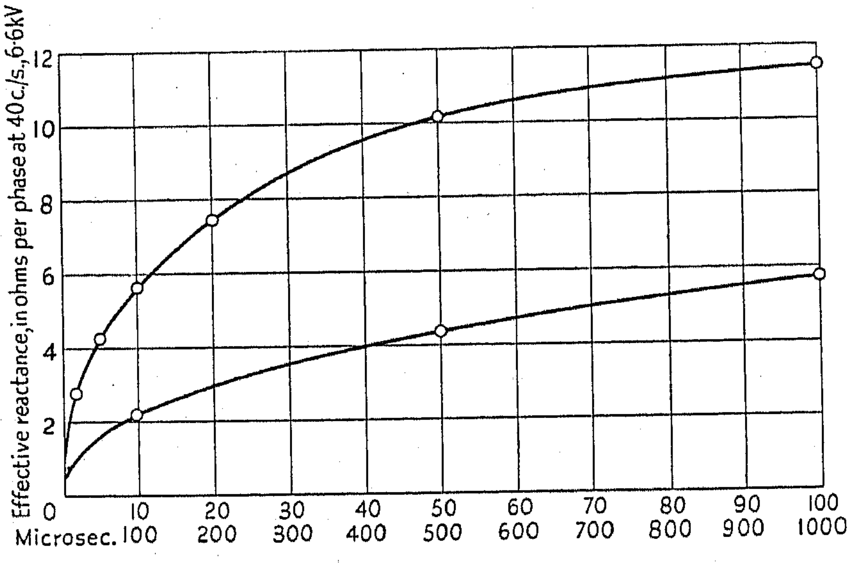

Fig. 19.—1 500-kVA 3-phase 6·6/0·425-kV transformer, reactance 5 %: zero phase-sequence exciting reactance as a function of time, shown to two different scales.

Similarly Curve B represents the overall reactance as a function of frequency.

(b) The reactances of the transformer and cables to the fault point.

The above applies only to the reactance of the transformer unit. It is necessary in addition to allow for the reactance of the cables from transformer to fault point.

As far as the positive phase-sequence reactance is concerned, the reactance of the short cables from transformer secondary to busbar, with that of the busbar itself, is negligible to the order of accuracy in which we are working, whilst the reactance of the cable from busbar to Switch B (Fig. 6) is 0·16 ohm at 40 c./s. referred to 6·6 kV.

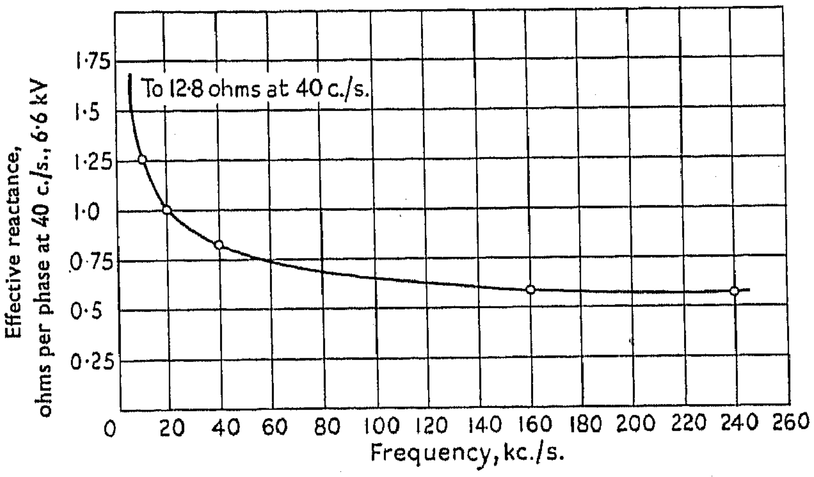

Fig. 20.—1 500-kVA 3-phase 6·6/0·425-kV transformer, 5 % reactance: zero phase-sequence exciting reactance as a function of frequency (based on assumptions mentioned in Appendix III).

The contribution of the cables to the zero phase-sequence reactance is difficult to assess. The sheaths of the 3-core cables between busbars and test switch were not earthed, except at the busbar end, the earth connection from the switch star-point being taken along a single cable parallel to the two 3-core cables, up to the busbar casing. Thereafter the path of the zero phase-sequence current was along the busbar casing, to the station earth bar, and to the transformer neutral. This reactance was not measured: but it is estimated that it was of the order of 0·6 ohm at 40 c./s. referred to 6·6 kV. The reactance values of these cables are included in Fig. 11.

(c) Capacitances.

The various capacitances contributing to the transient of restriking voltage are as shown in Fig. 12. None of these values was measured: all the figures given are calculated from dimensions of cables, etc., or estimated by comparison with measured figures for similar apparatus. It will be seen that all the positive phase-sequence capacitances have been taken as equal to the zero phase-sequence capacitances (i.e. effective capacitances to neutral per phase equal to effective capacitances to earth per phase) except in the case of the 3-core cable, where this is obviously not the case.

AMPLIFIER CHARACTERISTICS AT LOW FREQUENCIES, WITH PARTICULAR REFERENCE TO A NEW METHOD OF FREQUENCY COMPENSATION OF SINGLE STAGES*

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(*Paper first received* 18*th October*, 1939, *and in revised form* 9*th March*, 1940.)

SUMMARY

The paper deals with frequency characteristics of tetrode, pentode and triode amplifiers as determined by the impedances of the electrode supply circuits and interstage coupling circuits. Methods of complete compensation of the frequency characteristics due to these circuits are developed for single stages or single coupling circuits. These cases are of particular interest in the output stages of television receivers where the d.c. component of the signal is required.

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    (ii) Attenuation produced by screen impedance Z_s.
    (iii) Increased gain produced by anode impedance Z_a.
    (iv) Gain with anode and cathode impedances present.
    (v) Gain with anode and screen impedances present.
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Appendix.

(1) INTRODUCTION

The high-frequency characteristics of a resistance-coupled amplifier of the form shown in Fig. 1 are almost entirely decided by the values of the various stray capacitances of the circuit. At these frequencies it is assumed that the supply circuits are of zero impedance. At the low-frequency end of the amplifier range, however, the characteristics are mainly determined by (*a*) the values of R_g and C_g in the coupling circuits, and (*b*) the impedances of the supply decoupling circuits. The loss introduced by the grid coupling circuit of the amplifier shown in Fig. 1 is readily calculable and is illustrated by the curves in Fig. 2(*a*) for different values of R_g and C_g. The phase shift due to this coupling circuit is also shown.

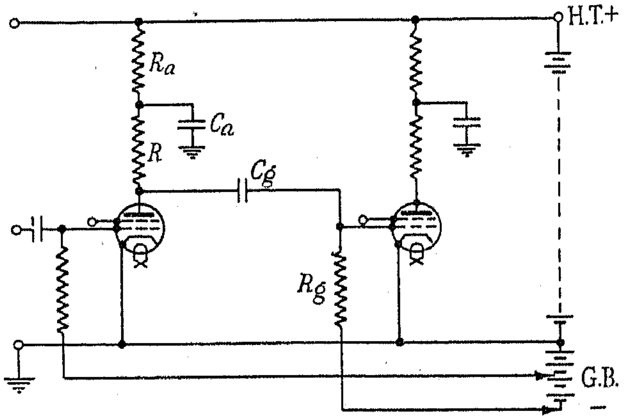

Fig. 1.—Basic resistance-capacitance-coupled amplifier.

Similarly, the increase in gain due to the anode decoupling circuit is given in Fig. 2(*b*), together with the phase shift introduced.

It has been shown in the past how the constants of these two parts of the circuit may be so adjusted that approximate compensation is obtained over part of the low-frequency range.[1, 2, 3, 4] This partial compensation is obtained by combining corresponding curves of Figs. 2(*a*) and 2(*b*), giving the resultant curves shown in Fig. 2(*c*). It is never possible, however, for this compensation to be exact, since, due to the grid coupling condenser, the voltage gain must fall to zero as it approaches zero frequency, requiring infinite gain for compensation with a consequent large phase shift in this region. Also, for a given minimum frequency, the conditions for minimum variation of gain and of phase shift with frequency do not correspond.

In some cases it is important that the amplifier characteristics remain more constant with frequency than can be obtained by the above method, particularly in the case of television picture frequency-amplifiers. These amplifiers often consist of a single stage whose frequency characteristics (gain and phase shift) should be substantially constant over a wide range extending from several megacycles down to zero. The levelness of characteristic at the upper end of this range is obtained by the use of some form of low-pass filter network, the details of which are not considered here.

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* Communication from the Staff of The Research Laboratories of The General Electric Co., Ltd., Wembley.

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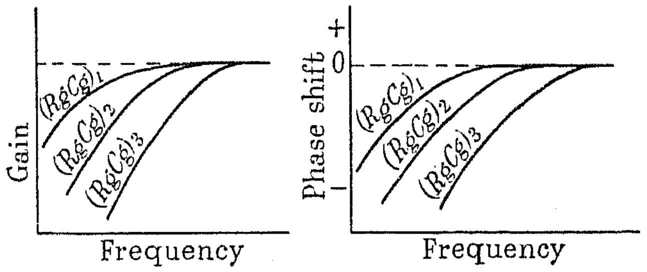
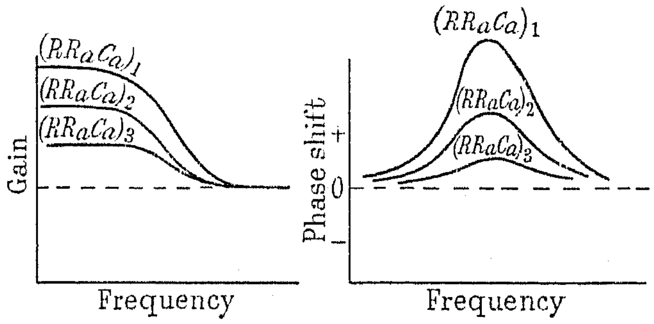
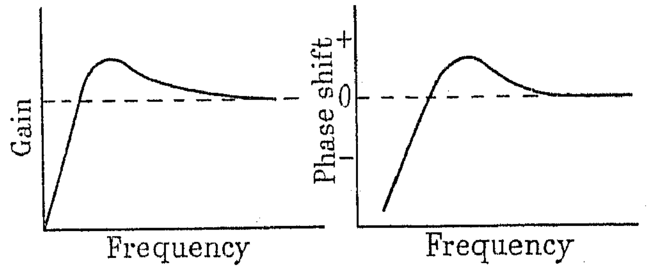


(*a*) Loss and phase shift introduced by grid coupling circuit.



(*b*) Gain and phase shift introduced by anode decoupling circuit.



(*c*) Partial l.f. compensation of resistance-capacitance-coupled amplifier.

Fig. 2.—Characteristics of normal resistance-capacitance-coupled amplifier.

The circuit of such a single-stage amplifier is shown in Fig. 3. This amplifier is loaded with the resistance R which, together with the inductance L and the valve capacitance C_v and the stray capacitance C_e determine the gain at the high-frequency end of the range; the effect of this inductance may be neglected at the low frequencies with which we are now concerned.

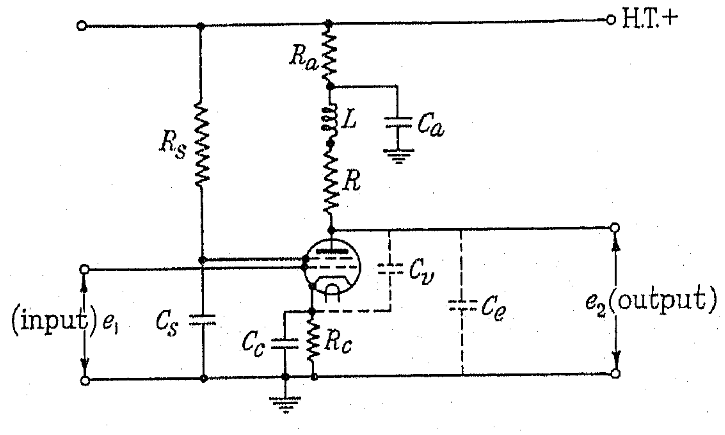


Fig. 3.—Single-stage television picture frequency amplifier.

The circuit is seen to include resistances R_c in the cathode, and R_s in the screen for the purpose of obtaining the correct voltages on these electrodes. The effect of the impedances formed by these resistances and their decoupling capacitances C_c and C_s has not been considered in the compensation described above. They do, however, modify the characteristics of the amplifier, owing to the negative feedback introduced in the manner shown in Fig. 4. These curves show the effect of the cathode and the screen circuits individually, all other supply circuits being of zero impedance.

It can be seen that both these curves are similar in form to those for the anode supply circuit shown in Fig. 2(*b*), but their variation with frequency is opposite in sign. It would therefore appear possible to adjust the constants of the circuit so that uniform gain (and phase delay) may be obtained at all low frequencies down to zero.

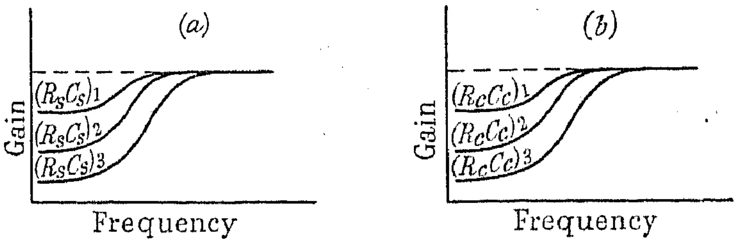


Fig. 4.—Feedback introduced by screen and cathode circuits.

(*a*) Screen circuit feedback. (*b*) Cathode circuit feedback.

When all three impedances (anode, screen and cathode) are present together, their effects on the amplifier frequency characteristics are interdependent, and these characteristics may not be determined in this case by simple addition of the curves in Figs. 2(*b*) and 4(*a*) and 4(*b*). This is dealt with more fully later.

It will be shown how, when all these impedances are present together, exact frequency correction may be realized. This correction is particularly applicable to single stages, i.e. to a valve and its associated anode, screen and cathode circuits. Complete correction can, of course, only be obtained with a directly coupled stage; if capacitance/resistance coupling networks are used these will still affect the frequency characteristic of the complete amplifier.

(2) CALCULATION OF AMPLIFIER FREQUENCY CHARACTERISTICS

There are two cases that are of particular practical interest—that of the tetrode or pentode amplifier valve, and that of the triode. These two cases differ in that the internal valve impedance can be considered infinitely large compared with its load impedance in the former case, and of the same order as, or smaller than, its load impedance in the latter.

The tetrode or pentode amplifier is of more interest for wide-band amplifiers, owing to the low grid-to-anode capacitance of the valve. This case will therefore be considered first.

The symbols used in the analysis are as follows:—

I_a, I_s = instantaneous values of the screen and anode currents respectively.

E_a, E_s, E_g = instantaneous values of the anode, screen and grid voltages measured with respect to cathode.

i_a, i_s = increments of anode and screen current (i.e. δI_a, δI_s).

e_a, e_s, e_g = anode, screen and grid voltage respectively, measured with respect to cathode.

e_1 = incremental input voltage—grid to earth.

e_2 = incremental output voltage—anode to earth.

$g = \partial I_a/\partial E_g$ = mutual conductance—grid to anode.

$g_s = \partial I_s/\partial E_g$ = mutual conductance—grid to screen.

$g_{sa} = \partial I_a/\partial E_s$ = mutual conductance—screen to anode.

$\sigma_s = \partial I_s/\partial E_s$ = screen conductance.

$\sigma_a = \partial I_a/\partial E_a$ = anode conductance.

Z_a, Z_s, Z_c = anode, screen, and cathode supply circuit impedances, respectively.

R = normal anode load, which is resistive over the frequency range considered.

g, g_s, g_{sa}, σ_s, σ_a = partial differentials taken with all variables, other than those concerned, kept constant. For small signals at any given working point, they will themselves be constants.

The small letters i_a, e_a, i_s, etc., are assumed to represent small positive increments, the other parameters being at the time kept constant. The absolute values of the voltages supplied to the anode, screen, etc., do not therefore enter into the analysis.

(a) Case of Tetrode or Pentode Amplifier

Since the dynamic anode-to-cathode impedance of a tetrode or pentode over the working range considered is normally very high, the value of σ_a can be neglected in comparison with the other circuit conductances. The effect of the anode voltage on the screen current is very small, and therefore g_{as}, the anode-to-screen conductance, is also negligible.

The operating conditions in the valve are then given by the five equations:—

$$i_a = ge_g + g_{sa}e_s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$e_2 = -\,i_a(R + Z_a) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$i_s = g_se_g + \sigma_se_s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$e_s = -\left[i_aZ_c + i_s(Z_s + Z_c)\right] \quad . \quad . \quad . \quad . \quad (4)$$

$$e_g = e_1 - (i_a + i_s)Z_c \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

relating the six variables i_a, i_s, e_s, e_g, e_1 and e_2 (Fig. 3).

By eliminating the first four of these variables we can obtain a relation between the remaining two, e_1 and e_2 giving the gain of the stage.

From (1), (4) and (5) we obtain

$$i_a = ge_1 - i_a(gZ_c + g_{sa}Z_c) - i_s(gZ_c + g_{sa}Z_c + g_{sa}Z_s) \quad (6)$$

and from (3), (4) and (5),

$$i_s = \frac{\left[1 + g_sZ_c + \sigma_s(Z_c + Z_s)\right]}{\left[g_se_1 - g_sZ_ci_a - \sigma_sZ_ci_a\right]}$$

Substituting in (6) and putting

$$g_sg_{sa}/g = \sigma_s^{*} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$i_a = \frac{ge_1}{1 + (g + g_s + g_{sa} + \sigma_s)Z_c + \sigma_sZ_s} \quad . \quad (8)$$

Thus, from equation (2),

$$\frac{e_2}{e_1} = -\frac{g(R + Z_a)}{1 + (g + g_s + g_{sa} + \sigma_s)Z_c + \sigma_sZ_s} = \mu' \quad (9)$$

where μ' is the stage gain obtained at frequencies where Z_a, Z_s, Z_c are appreciable. The negative sign indicates, of course, a phase change of 180°, introduced by the valve, which will be ignored in future consideration of the amplifier characteristics.

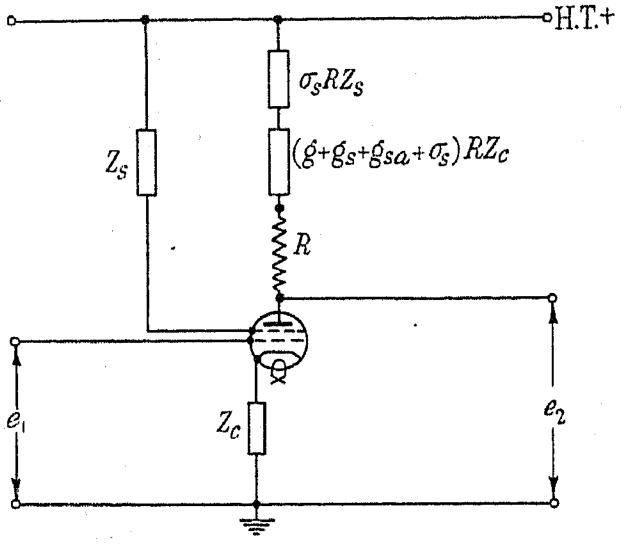


Fig. 5.—Frequency-corrected tetrode amplifier, using two anode decoupling circuits.

We shall consider firstly the effect on the stage gain of each of the three impedances Z_a, Z_s, and Z_c, separately.

(i) Attentuation produced by Cathode Impedance Z_c.

If feedback takes place in the cathode circuit only (i.e. if Z_a and $Z_s = 0$), the gain of the stage is [from equation (9)]

$$\mu_c = \frac{gR}{1 + G_cZ_c}$$

where $G_c = g + g_s + g_{sa} + \sigma_s$

The gain with no feedback (Z_a, Z_s and $Z_c = 0$) is $\mu = gR$. In the circuit at present under consideration, this is the stage gain at high frequencies, and may be taken as the datum.

The attenuation produced by the cathode impedance is, therefore,

$$\beta_c = 20\log_{10}|1 + G_cZ_c|\text{db.} \quad . \quad . \quad . \quad (10)$$

Now in the type of circuit with which we are concerned (Fig. 3) the impedance Z_c has the form

$$Z_c = \frac{R_c}{1 + j\omega R_cC_c}$$

---

* See Appendix.

Inserting this value of Z_c in equation (10),

$$\beta_c = 10 \log_{10} \frac{[1 + G_c R_c + \Omega_c^2]^2 + [G_c R_c \Omega_c]^2}{[1 + \Omega_c^2]^2} \text{db.} \quad (11)$$

where $\Omega_c = \omega R_c C_c$

(ii) Attenuation produced by Screen Impedance Z_s.

If feedback takes place in the screen circuit only (i.e. if Z_a and $Z_c = 0$) the gain is [from equation (9)]

$$\mu_s = \frac{gR}{1 + \sigma_s Z_s}$$

Again taking the high-frequency gain $\mu = gR$ as the datum, the attenuation produced by the screen impedance becomes

$$\beta_s = 20 \log_{10} |1 + \sigma_s Z_s| \text{ db.}$$

and inserting the value $Z_s = \dfrac{R_s}{1 + j\omega R_s C_s}$

we have

$$\beta_s = 10 \log_{10} \frac{[1 + \sigma_s R_s + \Omega_s^2]^2 + [\sigma_s R_s \Omega_s]^2}{[1 + \Omega_s^2]^2} \text{ db.} \quad . \quad (12)$$

where $\Omega_s = \omega R_s C_s$

(iii) Increased Gain Produced by Anode Impedance Z_a.

The value of the anode load is $(R + Z_a)$ and at high frequencies Z_a vanishes.

Again taking the high-frequency gain as the datum, the increase of gain produced by the anode circuit impedance Z_a is

$$\beta_a = 20 \log_{10} \left| \frac{R + Z_a}{R} \right| \text{ db.}$$

or inserting the value $Z_a = \dfrac{R_a}{1 + j\omega R_a C_a}$

we have

$$\beta_a = 10 \log_{10} \frac{\left[1 + \frac{R_a}{R} + \Omega_a^2\right]^2 + \left[\frac{R_a}{R}\Omega_a\right]^2}{[1 + \Omega_a^2]^2} \text{ db.} \quad . \quad (13)$$

where $\Omega_a = \omega R_a C_a$

It is seen that the three expressions (11), (12) and (13) are identical in form, and may be represented by the same function:—

$$\frac{[1 + P + \Omega^2]^2 + [P\Omega]^2}{[1 + \Omega^2]^2} \quad . \quad . \quad . \quad (14)$$

where P is $G_c R_c$, $\sigma_s R_s$ and R_a/R for the cathode, screen and anode circuits respectively.

Similarly, the phase-shift characteristics of the anode, screen and cathode circuits can be represented by a common expression.

If θ is the phase angle produced by either of these circuits, then

$$\theta = \arctan \frac{\pm \Omega}{1 + P + P\Omega^2} \quad . \quad . \quad . \quad (15)$$

where P has the same meanings as in (14). It should be noted that in the case of the anode decoupling circuit the phase shift is positive, and so the sign in equation (15) above will be negative in accordance with normal transmission practice. For the screen and cathode circuits the phase shift is negative and the positive sign of equation (15) should be taken. Thus the effects of either the anode, screen or cathode circuits acting separately may be represented graphically by plotting the expressions (14) and (15).

These curves are shown in Figs. 6 and 7. In the first figure the attenuation produced by either the screen or cathode circuits and the increased gain due to the anode circuit have been plotted in decibels against Ω for several values of P. Similarly, in the second figure the phase shift θ has been plotted against Ω for different values of P. As shown below, these curves may, under certain conditions, be used to determine the frequency characteristics of an amplifier when the effects of two or more of the circuits Z_a, Z_s and Z_c are present together.

(iv) Gain with anode and cathode impedances present (not necessarily of equal time-constant).

The stage gain at low frequencies was shown to be $g(R + Z_a)/(1 + G_c Z_c)$ [equation (9), $Z_s = 0$] and at high frequencies, gR. The resultant gain characteristic is then given by the expression

$$20 \log_{10} \left| \frac{R + Z_a}{R} \cdot \frac{1}{1 + G_c Z_c} \right|$$

The modulus is the ratio of the two moduli $|(R + Z_a)/R|$ and $|1 + G_c Z_c|$. The phase is the difference of the phase angles of these two quantities.

Thus the resultant gain or attenuation may be determined directly from the curves representing these moduli (Fig. 6), and the phase shift from Fig. 7. It should be noted that the Ω (or $RC\omega$) values will not correspond when the time-constants of Z_a and Z_c are not equal.

(v) Gain with anode and screen impedances present (not necessarily of equal time-constant).

The same argument applies in this case, the gain ratio being $|(R + Z_a)/R \,.\, 1/(1 + \sigma_s Z_s)|$ of which the phase and magnitude may be obtained as before.

(vi) Gain with screen and cathode impedances present of equal time-constant (not necessarily equal to that of the anode circuit).

In this case, since the time-constants of Z_s and Z_c are equal, we have for the gain ratio (again referring to gR as the datum)

$$\left| \frac{R + Z_a}{R} \cdot \frac{1}{1 + Z_c(G_c + \sigma_s k)} \right|$$

where $k = Z_s/Z_c$ ($= R_s/R_c$ if Z_s and Z_c have equal time-constants). The terms $|(R + Z_a)/R|$ and $|1 + Z_c(G_c + \sigma_s k)|$ may be obtained directly from the curves, using the parameters $P = R_a/R$ and $P = G_c R_c + \sigma_s R_s$.

(vii) Gain with anode, screen and cathode impedances, all of unequal time-constants.

The gain ratio is

$$|(R + Z_a)/R \,.\, 1/(1 + G_c Z_c + \sigma_s Z_s)| \quad . \quad . \quad (16)$$

Now since this expression involves the sum of two

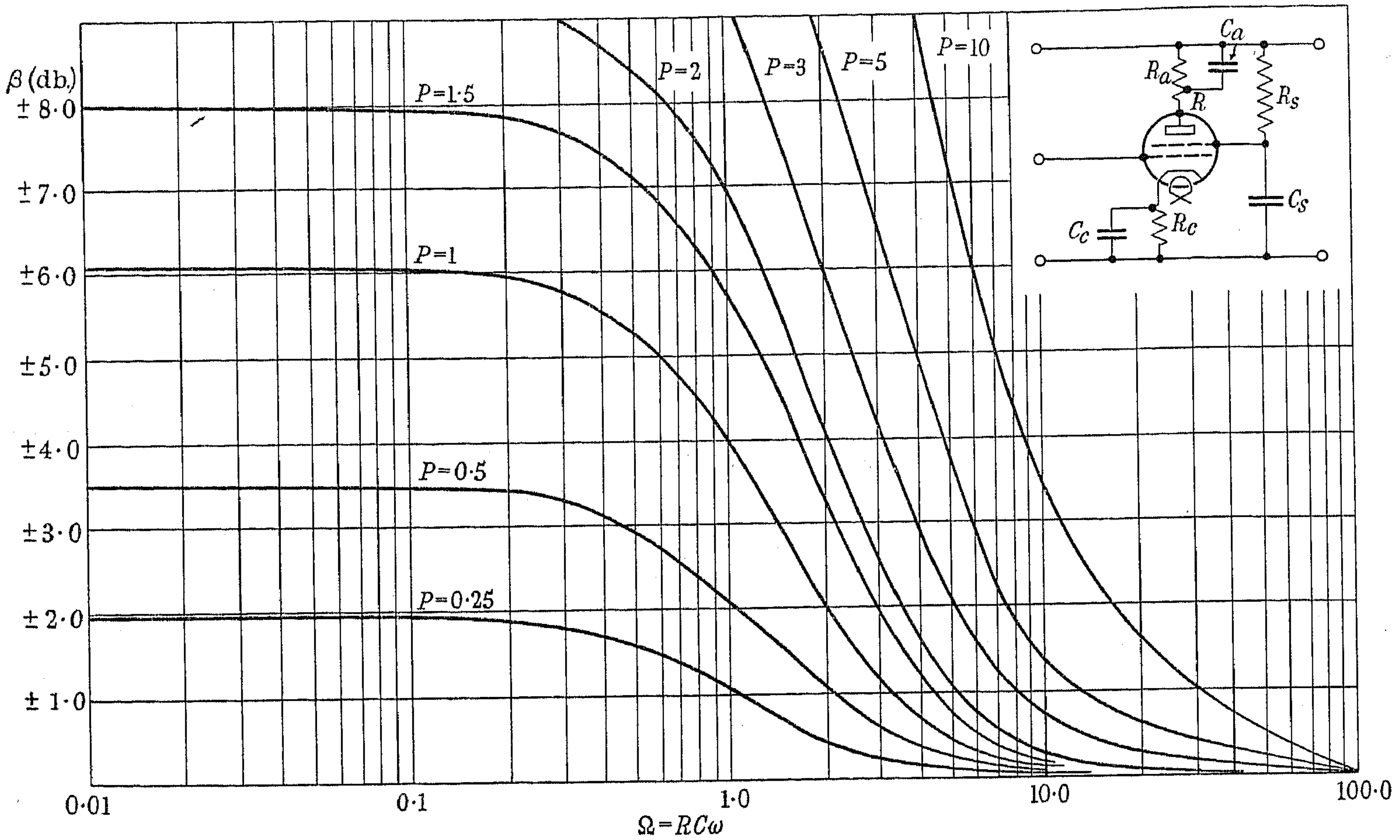


Fig. 6.—Amplifier gain characteristics.

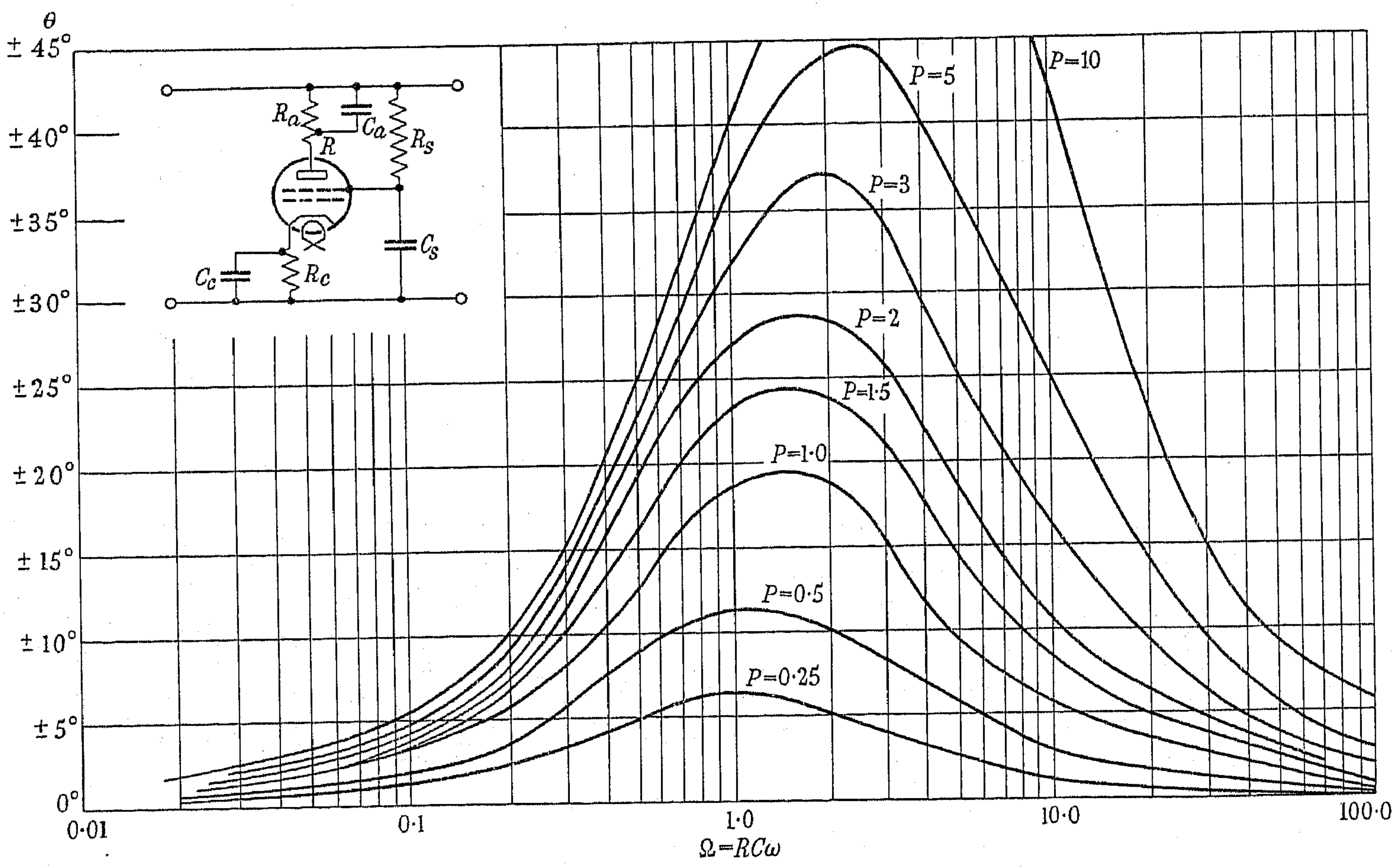


Fig. 7.—Amplifier phase-shift characteristics.

Values of P in Figs. 6 and 7:—

(1) Anode. $P = R_a/R$. Use positive db. and positive θ signs.
(2) Screen. $P = \sigma_s R_s$. Use negative db. and negative θ signs.
(3) Cathode. $P = G_c R_c$. Use negative db. and negative θ signs.

impedances of unequal time-constants, it cannot be represented by curves in two dimensions and so may not readily be determined graphically. However, a comparatively simple formula may be derived for calculating the gain and phase characteristics for any particular circuit arrangement, as follows.

The first term in the gain ratio given by (16), viz. $|R + Z_a)/R|$ may be determined from Fig. 6, and we require to know the second term $|1 + G_cZ_c + \sigma_sZ_s|$.

Inserting the values of Z_s and Z_c and rationalizing, this becomes

$$\left|\left[1 + \frac{G_cR_c}{(1 + \Omega_c^2)} + \frac{\sigma_sR_s}{(1 + \Omega_s^2)}\right] - j\left[\frac{\Omega_cG_cR_c}{(1 + \Omega_c^2)} + \frac{\Omega_s\sigma_sR_s}{(1 + \Omega_s^2)}\right]\right| \quad . \quad . \quad . \quad (17)$$

where again $\Omega_c = \omega R_cC_c$

$\Omega_s = \omega R_sC_s$

Taking the modulus, the loss introduced by the screen and cathode circuits together (with dissimilar time-constants) is

$$10 \log_{10} \left[(1 + A + B)^2 + (\Omega_cA + \Omega_sB)^2\right] \text{db.} \quad . \quad (18)$$

where $A = \dfrac{G_cR_c}{1 + \Omega_c^2}$ and $B = \dfrac{\sigma_sR_s}{1 + \Omega_s^2}$

Similarly the phase angle may be shown to be [from equation (17)]:—

$$\theta = \text{arc tan}\,\frac{\Omega_cA + \Omega_sB}{1 + A + B} \quad . \quad . \quad . \quad (19)$$

Then since the gain introduced by the anode impedance Z_a and the corresponding phase shift may be obtained from Figs. 6 and 7, the overall gain and phase shift characteristics of such an amplifier, where Z_a, Z_s, and Z_c all have different time-constants, may be determined by obtaining values of the expressions (18) and (19) for different values of ω and combining with values of $20 \log_{10} |(R + Z_a)/R|$ and θ as obtained from the curves.

(b) Case of Triode Amplifier

It was assumed in the last Section that the valves concerned were of sufficiently high impedance for their anode conductances to be considered zero in the calculations. This is, of course, not justifiable for a triode, and the characteristics of such a stage will now be calculated.

The circuit is shown in Fig. 8, where Z_c is an impedance in the cathode lead, normally a biasing circuit, and Z_a is an impedance in the anode lead, in series with R, the normal resistive load, usually the supply decoupling circuit.

Let $\sigma_a = \partial i_a/\partial e_a$, the anode conductance.

Again assuming linear characteristics, we have the following equations:—

$$i_a = ge_g + \sigma_ae_a$$
$$e_g = e_1 - i_aZ_c$$
$$e_a = -\,i_a(R + Z_a + Z_c)$$
$$e_2 = -\,i_a(R + Z_a)$$

giving $$\frac{e_2}{e_1} = \mu' = \frac{g(R + Z_a)}{1 + gZ_c + \sigma_a(R + Z_a + Z_c)} \quad . \quad (20)$$

Now at high frequencies the impedances Z_a and Z_c both tend to zero and the gain then becomes

$$\mu = \frac{gR}{1 + \sigma_aR} \quad . \quad . \quad . \quad . \quad (21)$$

Then the change in gain introduced at low frequencies by these two impedances may be written as:—

$$20 \log_{10} \left|\left[\frac{R + Z_a}{R}\right]\left[\frac{1 + \sigma_aR}{1 + gZ_c + \sigma_a(R + Z_a + Z_c)}\right]\right| \quad (22)$$

The modulus and angle of the first bracketed expression are again given in Figs. 6 and 7. We require those of the second expression.

Now, $$Z_a = \frac{R_a}{1 + j\omega R_aC_a}$$

and $$Z_c = \frac{R_c}{1 + j\omega R_cC_c}$$

Inserting these values and taking the modulus, we have for the second bracketed expression in equation (22)

$$10 \log_{10} \left[\left(\frac{1}{1 + \sigma_aR}\right)^2\left\{\left((1 + \sigma_aR_a) + \frac{\sigma_aR_a}{(1 + \Omega_a^2)} + \frac{R_c(g + \sigma_a)}{(1 + \Omega_c^2)}\right)^2 + \left(\frac{\sigma_aR_a\Omega_a}{(1 + \Omega_a^2)} + \frac{R_c\Omega_c(g + \sigma_a)}{(1 + \Omega_c^2)}\right)^2\right\}\right] \quad . \quad . \quad (23)$$

Then the phase angle is given by

$$\theta = \text{arc tan}\left[\frac{\sigma_aR_a\Omega_a(1 + \Omega_c^2) + R_c\Omega_c\,(g + \sigma_a)(1 + \Omega_a^2)}{(1 + \sigma_aR)(1 + \Omega_a^2)(1 + \Omega_c^2) + \sigma_aR_a(1 + \Omega_c^2) + R_c(g + \sigma_a)(1 + \Omega_a^2)}\right] \quad . \quad . \quad . \quad (24)$$

which is a negative angle. Also

$$\Omega_a = \omega R_aC_a$$
$$\text{and } \Omega_c = \omega R_cC_c$$

Although these expressions appear unwieldy, it must be remembered that, for any particular circuit, all the terms are constants except ω. These equations cannot be fully represented by curves in two dimensions. Then in order to calculate the characteristics of such a triode amplifier when Z_a and Z_c have different time-constants,

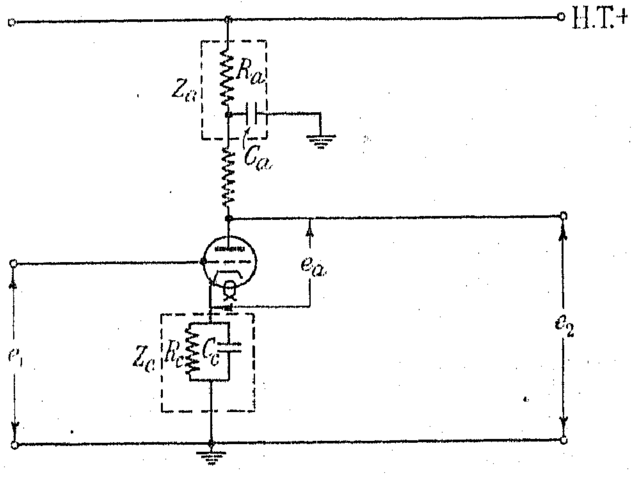


Fig. 8.—Single-stage triode amplifier.

the term $|(R + Z_a)/R|$ and its angle are obtained from Figs. 6 and 7, while the other term

$$\left|\frac{1 + \sigma_a R}{1 + gZ_c + \sigma_a + (R + Z_a + Z_c)}\right|$$

and its angle are calculated from equations (23) and (24), and the results combined.

If the impedances Z_a and Z_c have equal time-constants, the work of deriving the gain and phase characteristics is greatly simplified.

In this case, $\Omega_a = \Omega_c = \Omega$.

Then the expressions (23) and (24) simplify to

$$10 \log_{10} \frac{(1 + P + \Omega^2)^2 + (P\Omega)^2}{(1 + \Omega^2)^2} \text{ db.}$$

and $$\theta = \text{arc tan} \frac{-\Omega}{1 + P + P\Omega^2}$$

where $$P = \frac{\sigma_a R_a + (g + \sigma_a)R_c}{1 + \sigma_a R}$$

and is a constant for any particular circuit. Now these expressions are seen to be identical with (14) and (15) in Section 2(*a*)(iii) and are therefore represented by the curves of Figs. 6 and 7, so that in this special case the gain and phase characteristics may be determined entirely from these curves without further calculation.

(3) FREQUENCY CORRECTION OF AMPLIFIER STAGES

The similarity of form of the frequency characteristics introduced by the cathode, screen and anode circuits suggests that frequency correction may be obtainable by adjustment of the values of these three parameters. The conditions under which this correction may be realized are readily determined from the previous calculations. It will be seen, however, from the following that frequency correction may be obtained when the impedances Z_a, Z_s and Z_c are not necessarily of the form assumed in the preceding calculations.

(a) Tetrode Amplifier

(i) Conditions for frequency correction.

In Section 2(*a*) the gain of a tetrode amplifier stage was calculated, involving the impedances Z_a, Z_s and Z_c (equation 9).

If these impedances are not present, the gain would be constant and of value

$$\mu = gR \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

and the phase shift would be zero.

We shall now show that the gain can still have this value even when Z_a, Z_s and Z_c are appreciable.

The condition for this is obtained by equating μ and μ'

or $$\mu' = gR \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Then, from equations (9) and (26),

$$Z_a = (g + g_s + g_{sa} + \sigma_s)RZ_c + (\sigma_s)RZ_s \quad . \quad (27)$$

Thus, the impedance Z_a in the anode circuit may consist of two impedances in series, as shown in Fig. 5, one having the frequency characteristic of Z_c and the other the characteristic of Z_s, such that the increased gain produced may exactly compensate the negative feedback introduced by the screen and cathode impedances. The gain of the stage at all frequencies will now be gR, and the phase shift zero. It is seen that Z_c and Z_s may have any impedance forms, similar or not, and not necessarily of resistance-capacitance form as assumed in the preceding calculations.

(ii) Special Cases.

If $Z_c = 0$, i.e. the cathode is maintained at constant potential, for example when running the valve at zero bias, or with a separate bias supply for the control grid.

Then from equation (27), $Z_a = \sigma_s RZ_s$; thus the screen and anode circuits alone can compensate one another.

If $Z_s = 0$, i.e. the screen is kept at constant potential, as when running the screen at the H.T. line voltage from a low-impedance supply circuit. Again from equation (27), exact compensation of cathode and anode circuits is obtained when $Z_a = (g + g_s + g_{sa} + \sigma_s)RZ_c$. For practical purposes, g_{sa} and σ_s are usually negligible compared with g and g_s, and a sufficiently accurate approximation can often be obtained even by neglecting all conductances except g.

(iii) Reduction of Z_a to a Single Impedance.

We have seen that in the most general case, for frequency correction, Z_a consists of two impedances in series, depending upon the screen and cathode impedances Z_s and Z_c. Z_a may be reduced to a single impedance in a special case as follows:—

Equation (27) may be written

$$Z_a = Z_c\left[(g + g_s + g_{sa} + \sigma_s)R + \frac{Z_s}{Z_c}\sigma_s R\right] \quad . \quad (28)$$

Now for the expression in brackets to be a real constant, Z_s/Z_c must be a constant.

If $k = Z_s/Z_c$ [as in Section 2(*a*)(vi)], we have:—

$$Z_a = Z_c[(g + g_s + g_{sa} + \sigma_s)R + \sigma_s kR] \quad . \quad (29)$$

If then, an impedance Z_a as given by the above equation is introduced into the valve anode circuit, the amplification of the stage will be rendered independent of frequency and equal to gR, and the phase shift will be zero. It is seen that special conditions have been introduced concerning Z_s and Z_c. If the ratio Z_s/Z_c is to be a real constant, then both Z_s and Z_c must be of the same impedance form. In the most usual case, Z_s and Z_c will consist of capacitances and resistances in parallel for decoupling purposes as shown in Fig. 3, and in this case their time-constants must be equal,

i.e. $$k = \frac{Z_s}{Z_c} = \frac{R_s}{R_c} = \frac{C_c}{C_s} \quad . \quad . \quad . \quad . \quad (30)$$

But from equation (29), Z_a must have the same time-constant as Z_c.

Then $$R_aC_a = R_cC_c = R_sC_s \quad . \quad . \quad . \quad . \quad (31)$$

Then the individual values of R_a and C_a are given as:—

$$\left.\begin{aligned} R_a &= R_c[(g + g_s + g_{sa} + \sigma_s)R + \sigma_s kR] \\ C_a &= C_c\left[\frac{1}{(g + g_s + g_{sa} + \sigma_s)R + \sigma_s kR}\right] \end{aligned}\right\} \quad . \quad (32)$$

for exact correction of amplitude and phase variation with frequency.

If the condition $Z_s/Z_c = k$ cannot be realized owing to other conditions being imposed on the circuit, then the value of Z_a is given by the more general equation (27) as two impedances in series having different time-constants.

(iv) Practical Example.

The low-frequency correction of a typical television picture-frequency receiver output stage will now be considered.

The valve used is a high-slope tetrode, the Osram K.T.Z.41, having the following constants:—

$$\begin{aligned} g &= 10 \times 10^{-3} \text{ amp./volt} \\ g_s &= 2{\cdot}5 \times 10^{-3} \text{ amp./volt} \\ g_{sa} &= 0{\cdot}2 \times 10^{-3} \text{ amp./volt} \\ \sigma_s &= 0{\cdot}05 \times 10^{-3} \text{ amp./volt} \end{aligned}$$

It can be seen that g and $g_s >> g_{sa}$ and σ_s. Assume the working point to be,

$$\left.\begin{aligned} E_0 &= -1 \\ E_s &= 200 \end{aligned}\right\} \begin{aligned} I_a &= 16 \text{ mA} \\ I_s &= 4 \text{ mA} \end{aligned}$$

H.T. supply voltage = 260

The anode voltage is normally unimportant, provided the valve is working, as assumed, on that part of the characteristic where the anode-cathode conductance is negligible. Then the cathode bias resistance R_c required to give these conditions = 50 ohms. Screen dropping resistance required, R_s = 15 000 ohms. Then from equation (30), k = 300.

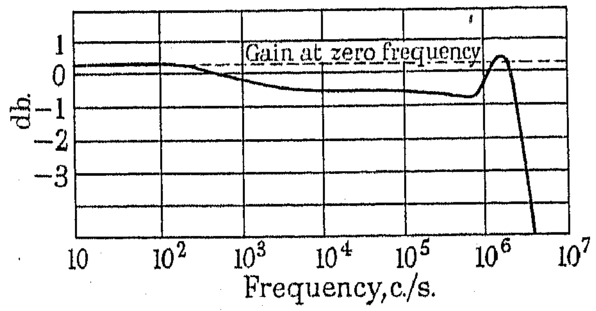


Fig. 9.—Measured characteristic of corrected tetrode amplifier stage.

The valve anode load must now be fixed. In a wide-band amplifier this is normally determined by the required high-frequency characteristic and the inherent circuit and valve capacitances. A suitable value of anode load (R) could be 3 000 ohms. Then, from equation (32), we may determine the value of R_a.

$$R_a = 50\left[\left(\frac{12{\cdot}75}{1\,000} \times 3\,000\right) + (0{\cdot}05 \times 10^{-3} \times 300 \times 3\,000)\right]$$
$$= 4\,160 \text{ ohms.}$$

Now the condenser values may be determined after one of them has been fixed. With a screen decoupling capacitance (C_s) of $0{\cdot}25\ \mu$F, the values of the anode and cathode decoupling condensers may be found from equation (31) (equating time constants).

$$R_s C_s = 3\,750 \text{ microseconds,}$$

giving
$$C_c = \frac{3\,750}{50} \times 10^{-6} = 75\ \mu\text{F}.$$

and
$$C_a = \frac{3\,750}{4\,160} \times 10^{-6} = 0{\cdot}2\ \mu\text{F}.$$

Then the gain of the above stage will be $\mu = gR = 30$ from zero up to the frequency at which gain is appreciably affected by stray circuit capacitance.

Fig. 9 shows the gain characteristic measured on an amplifier compensated as given above.

(b) Triode Amplifier

(i) Conditions for Frequency Correction.

The gain of a triode amplifier is given by equation (20), where Z_a and Z_c may have any impedance form.

In the absence of a cathode impedance Z_c and anode supply circuit impedance Z_a the gain would be:—

$$\mu = \frac{gR}{1 + \sigma_a R} \qquad \text{[eqn. (21)]}$$

which is independent of frequency.

In practical circuits the impedances Z_a and Z_c usually vanish at some frequency, and the gain at that frequency is then given by this equation.

In order to make the gain μ', as given by equation (20), independent of frequency, we can equate it to μ,

or
$$\frac{g(R + Z_a)}{[1 + gZ_c + \sigma_a(R + Z_a + Z_c)]} = \frac{gR}{[1 + \sigma_a R]} \quad . \quad . \quad (33)$$

giving the condition

$$Z_a = (g + \sigma_a)RZ_c \quad . \quad . \quad . \quad . \quad . \quad (34)$$

Thus, for the amplifier to have constant gain and zero phase-shift, the anode impedance Z_a must have the same impedance form as Z_c and must be $(g + \sigma_a)R$ times the magnitude. The gain of the stage is then given by equation (21) at all frequencies.

(4) GRID COUPLING CIRCUITS

(a) Multistage Amplifiers

As previously mentioned, the above method of frequency correction is particularly applicable to single amplifier stages, for example those commonly used as vision output stages in television receivers. If more than one stage is required in cascade, the d.c. coupling necessary between successive stages involves difficulties in the supply circuits.

Methods have previously been described whereby partial compensation may be obtained between resistance-capacitance coupling circuit and anode supply circuit characteristics.

In order to obtain satisfactory frequency response, this involves very high time-constants in the anode circuits, and consequently inconveniently large condenser values.

It has been found preferable in resistance-capacitance-coupled amplifiers to correct the anode, screen and cathode circuits of each stage separately, as described in Section (3), since the time-constants may then be made of reasonably small values: it is possible alternatively to compensate one anode circuit by preceding or following cathode and screen circuits. The characteristic of the complete amplifier is then only limited by the time-constants of the grid coupling circuits. These may usually be made long with conveniently small capacitance values. The characteristics of the resistance-capacitance coupling circuits are given by Fig. 10.

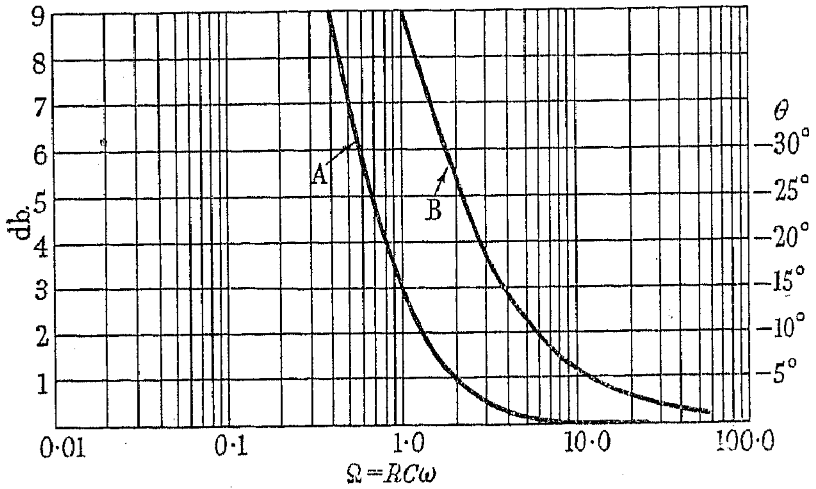


Fig. 10.—(A) loss and (B) phase shift introduced by grid coupling circuit.

Such an amplifier by itself, of course, does not amplify down to direct current as generally required for television purposes. This latter characteristic may be obtained, however, by one of the well-known " D.C. re-insertion " methods, since the vision signal normally supplies the repeated datum essential to this method.

(b) Corrected Coupling Circuits

(i) Methods of Correction.

While it is not possible to obtain correction down to direct current with normal resistance-capacitance inter-stage couplings, there are other forms of circuit which may be used. One method is illustrated in Fig. 11. In this arrangement the circuit elements R_2, C_2, R_3 are made equal to KR_1, KC_1 and KR respectively, where K is some numerical constant. Then, neglecting any parts of the circuit other than these elements, the gain of the stage at all frequencies is

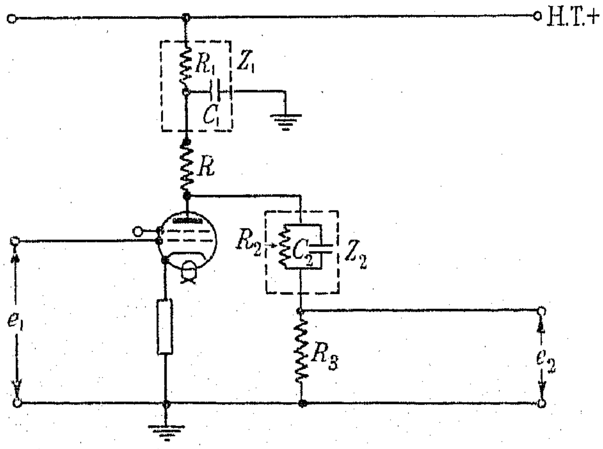


Fig. 11.—Amplifier stage with coupling circuit which corrects effect of anode decoupling circuit.

$$\frac{e_2}{e_1} = g(R + Z_1)\cdot\frac{R_3}{(R_3 + Z_2)}$$

$$= \frac{gR_3}{K} = gR$$

This arrangement, it will be seen, provides correction of the anode circuit characteristic by that of the following grid coupling circuit.

A circuit is shown in Fig. 12 which has been found particularly useful. This provides exact correction between the characteristics of the coupling circuit and the following cathode circuit, and so may be used when there is no anode decoupling circuit to correct for the cathode feedback.

The most important case is that illustrated in Fig. 12 of coupling to the modulator of a cathode-ray tube.

The resistance R_4 provides the bias for the tube, while C_4 is its decoupling condenser. The impedance of this circuit will be denoted by Z_4, and similarly R_3 and C_3 in parallel by Z_3.

In some arrangements, the tube would be biased from a potentiometer, and in this case R_4 would have the value of the two parts of the potentiometer, on either side of the tapping point, in parallel. We have to find suitable values for R_1, R_2, R_3 and C_3 to make the ratio e_g/e_1 a constant independent of frequency, since it is assumed that the preceding valve stage has already been frequency-corrected.

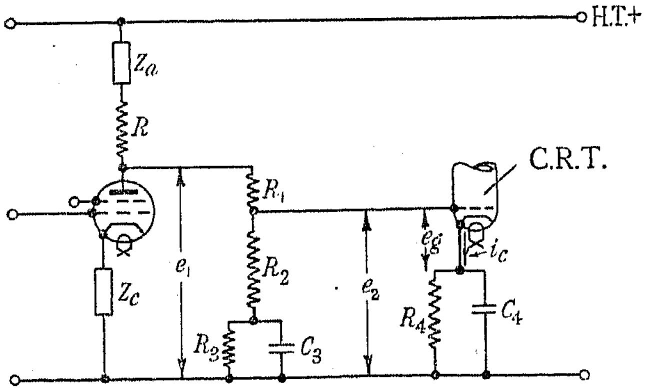


Fig. 12.—Amplifier stage with coupling circuit to correct for cathode biasing circuit of following valve.

It will first be assumed that the modulator (grid) takes zero current. Then, assuming small voltage and current displacements,

e_g = grid/cathode voltage increment

i_c = cathode current increment

$$g = \frac{\partial I_c}{\partial E_g} = \frac{i_c}{e_g}$$

e_1 = input voltage to circuit

we have the following equations

$$i_c = ge_g$$

$$e_g = e_2 - i_c Z_4$$

$$\frac{e_2}{e_1} = \frac{R_2 + Z_3}{R_1 + R_2 + Z_3}$$

giving
$$\frac{e_1}{e_g} = \frac{(R_1 + R_2 + Z_3)(1 + gZ_4)}{(R_2 + Z_3)} \quad . \quad . \quad (35)$$

and it is required to render this ratio independent of frequency.

At very high frequencies the impedances Z_3 and Z_4 vanish, giving the ratio

$$\frac{e_1}{e_g} = \frac{R_1 + R_2}{R_2} \quad . \quad . \quad . \quad . \quad . \quad (36)$$

Then, equating the values of e_1/e_g as given by equations (35) and (36) gives the condition

$$Z_3 = (R_1 + R_2)\left[\frac{-g\frac{R_2}{R_1}\cdot Z_4}{g\frac{R_2}{R_1}\cdot Z_4 - 1}\right] \quad . \quad . \quad (37)$$

for e_1/e_g to have the constant value $(R_1 + R_2)/R_2$ at all frequencies. Since the ratio e_1/e_g is a real constant, it follows that the phase shift between e_1 and e_g must be zero.

Now this impedance Z_3 given by equation (37) is seen to be equivalent to a negative resistance $-(R_1 + R_2)$ in parallel with an impedance $\left[(R_1 + R_2)g(R_2/R_1)\right]Z_4$. This latter impedance obviously has the same time-constant as Z_4.

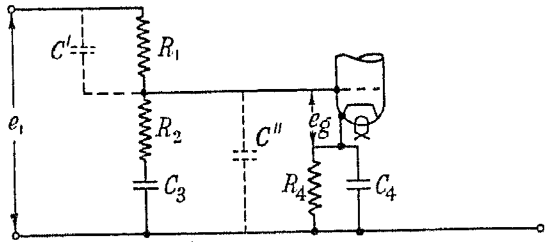


Fig. 13.—Coupling circuit in the limiting condition when $g\frac{R_2}{R_1}R_4 = 1$.

Thus the total effective parallel resistance of Z_3 is

$$R_3 = \frac{(R_1 + R_2)\left(g\frac{R_2}{R_1}\cdot R_4\right)}{1 - \left(g\frac{R_2}{R_1}\cdot R_4\right)}$$

so, for this to be a positive resistance, we have the condition

$$g\frac{R_2}{R_1}\cdot R_4 \leqslant 1$$

the limiting case being when

$$R_3 = \infty,$$

$$g\frac{R_2}{R_1}\cdot R_4 = 1 \quad . \quad . \quad . \quad . \quad (38)$$

C_3, however, still remains finite.

$$C_3 = \frac{R_4C_4}{(R_1 + R_2)}$$

This condition is shown in Fig. 13. The capacitance C' should be neglected at the moment, but reference will be made to it later.

In the limiting case, as given by equation (38), we have

$$\frac{R_1}{R_2} = gR_4$$

and
$$(R_1 + R_2) = \frac{R_4C_4}{C_3}$$

Thus the resistance $(R_1 + R_2)$ may be a potentiometer with the tube modulator joined to the tapping point, which may then be varied to suit the value of g, the grid-to-cathode mutual conductance of the tube. The whole compensating circuit should be made of impedance sufficiently high not to affect appreciably the operation of the correcting anode circuit of the preceding valve.

(ii) Effect of Grid Current.

Under working conditions the control electrode (modulator or grid) may take an appreciable current, and this somewhat modifies the operation of the circuit. Let σ_g represent the conductance of this electrode, i_g the electrode current displacement, and i_c the cathode current displacement (which includes i_g).

Then the effect of i_g is, in short, to make the ratio

$$\frac{e_1}{e_g} = \frac{(R_1 + R_2 + Z_3)(1 + gZ_4)}{(R_2 + Z_3)} + \sigma_g R_1$$

where $\sigma_g = \frac{i_g}{e_g}$

Comparing this ratio with that given by equation (35), (i.e. when i_g is absent), it is seen that, except for the term $\sigma_g R_1$ which is independent of frequency, the two are identical. Thus the presence of modulator or grid current will not affect the frequency characteristic of the circuit, but will increase the step-down ratio of the potentiometer circuit between the anode of one stage and the grid of the next.

This assumes that the grid-to-cathode conductance can be represented by a constant. In practice this is not strictly true, owing to non-linearity of the modulator current characteristic, and the compensation should vary with the voltage on the grid.

(iii) H.F. Distortion.

Since the resistances R_1 and R_2 must usually be fairly large the input capacitance (C'' in Fig. 13) of the grid/cathode system of the cathode-ray tube will introduce some amplitude and phase distortion at high frequencies. This distortion may be overcome by placing a suitable small capacitance (C' in Fig. 13) across R_1, such that the time-constant R_1C' equals that of the input grid/cathode circuit

or
$$R_1C' = \frac{R_2C''}{1 + \sigma_g R_2}$$

This time-constant is so short that the low-frequency correction is unaffected.

(5) CONCLUSIONS

In the preceding analysis, the circuit operation has been considered from the point of view of the steady-state conditions, since this gives most readily the desired relations between circuit elements. It is, of course, true to say that an amplifier which has uniform gain and zero phase-shift with frequency has also a perfect transient response.

Owing to the nature of a television signal, defects in amplifier response appear most noticeably in practice as distortion of transients. Thus it has been found most satisfactory, in testing this type of amplifier practically, to use what is effectively a transient method of examining the response. Square waves of low frequency provide a suitable test signal, and these may be conveniently generated by a rotating-disc light chopper, in conjunction with a photocell and amplifier, or with an electron multiplier. The squareness of the generated a.c. wave form may be examined by an oscillograph, and in a similar way the distortion introduced by the amplifier under test may be observed. This type of signal is particularly sensitive to small changes of phase, and shows up the distortion in a way characteristic of its effect on the television picture. Serious low-frequency distortion in television amplifiers may produce " shading " of the picture in a vertical direction, an effect which can be very objectionable. Variations of high-frequency response are also easily detectable by this test, as for example " overswinging " after sharp input changes.

Practical tests have been made by this means on amplifying circuits designed according to the methods described, and have shown that perfectly satisfactory transient response can be obtained using commercial components with their normal tolerances.

APPENDIX

In developing the expression for the gain of the tetrode amplifier stage, a relation between the valve constants was assumed, namely $g_s g_{sa} = g\sigma_s$ [equation (7)], and a short proof of this should be given.

The following valve equations were used:—

$$i_a = g e_g + g_{sa} e_s \quad . \quad . \quad . \quad [\text{eqn. (1)}]$$

and

$$i_s = g_s e_g + \sigma_s e_s \quad . \quad . \quad . \quad [\text{eqn. (3)}]$$

Let the two increments i_a and i_s be zero, in turn, then:—

$$\left.\begin{aligned} \frac{e_g}{e_s}\,(\text{with } I_a \text{ constant}) &= -\frac{g_{sa}}{g} \\ \text{and}\quad \frac{e_g}{e_s}\,(\text{with } I_s \text{ constant}) &= -\frac{\sigma_s}{g_s} \end{aligned}\right\} \quad . \quad . \quad (39)$$

But

$$\frac{e_g}{e_s}\,(\text{with } I_a \text{ constant}) = \left(\frac{\partial E_g}{\partial E_s}\right)_{I_a}$$

$$\frac{e_g}{e_s}\,(\text{with } I_s \text{ constant}) = \left(\frac{\partial E_g}{\partial E_s}\right)_{I_s}$$

and so for the required relation between the valve constants to be true, these two partial differentials must be equal.

Now the following three theorems, which are true in practical cases, will be assumed:—

(*a*) If E_a, E_g and E_s are increased (numerically) in the same ratio (say to aE_a, aE_g, aE_s), then the ratio I_s/I_a is unchanged.

(*b*) I_s and I_a are independent of E_a (this has already been assumed).

(*c*) The ratio I_s/I_a is independent of E_g. This is true for valves with no appreciable " focusing " effect, but is not strictly true in the case of " beam " valves. In this case, however, the effect of the screen may usually be neglected.

Then, let E_a, E_g and E_s be increased as in (*a*). I_s/I_a is unchanged.

Now let E_a be restored: I_s/I_a still unchanged [see (*b*)]. Then let E_g be restored: I_s/I_a still unchanged [see (*c*)]. Hence for all changes of E_a, E_g or E_s, the ratio I_s/I_a is unchanged.

Hence the variations of E_g and E_s which give constant I_a will also give constant I_s.

Thus

$$\left(\frac{\partial E_g}{\partial E_s}\right)_{I_s} \equiv \left(\frac{\partial E_g}{\partial E_s}\right)_{I_a}$$

giving, from equation (39),

$$\frac{g_{sa}}{g} = \frac{\sigma_s}{g_s}$$

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A VISUAL SELECTIVITY METER WITH A UNIFORM DECIBEL SCALE*

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(*Paper first received* 27*th October*, 1939, *and in revised form* 13*th March*, 1940.)

SUMMARY

Visual examination of the selectivity or frequency response of a filter by means of a frequency-modulated oscillator and cathode-ray tube is well known, but few attempts have been made to produce a selectivity curve to a decibel scale. A very successful method, which depends on A.G.C.‡ action (virtually negative feedback), has been developed to give logarithmic delineation of frequency response, and the apparatus is described with particular reference to decibel scale production. The carrier or mid-frequency range of the instrument is capable of variation from 50 to 1 500 kc./s., and four frequency-modulation ranges, giving band widths of 100, 50, 20 and 10 kc./s. are possible. The decibel frequency response scale is "linear" over a range of 60 db. Check tests at three different carrier frequencies, 1 500, 500 and 100 kc./s., are described and show the performance of the apparatus to be satisfactory and its degree of accuracy to be good.

INTRODUCTION

Instruction and research work in connection with radio-frequency filters and tuned circuits having a fixed or variable mid-frequency, are greatly facilitated if apparatus is available for the visual examination of the frequency response over the pass band and the attenuation regions on either side of this band. Such equipment usually comprises a frequency-modulated source supplying the input voltage to the test circuit, an amplifier after the test circuit, a detector and an amplifier, the output from which is connected to the Y plates of a cathode-ray tube. A suitable voltage, connected to the X plates to provide the frequency base, is used to produce frequency modulation of the test frequency. The frequency response of the test circuit should preferably be delineated logarithmically so as to give a decibel ratio-selectivity curve, and a very successful method of decibel delineation, which has been developed in the Marconi School of Wireless Communication, is described in this paper. For completeness, a brief description of the visual selectivity meter is given before the detailed treatment of the method of decibel delineation.

THE COMPLETE EQUIPMENT

A schematic diagram of the complete apparatus is shown in Fig. 1. A gas-filled valve generates the frequency base voltage—of saw-tooth shape—which is supplied to the frequency modulator and in push-pull to the X plates of the cathode-ray tube.

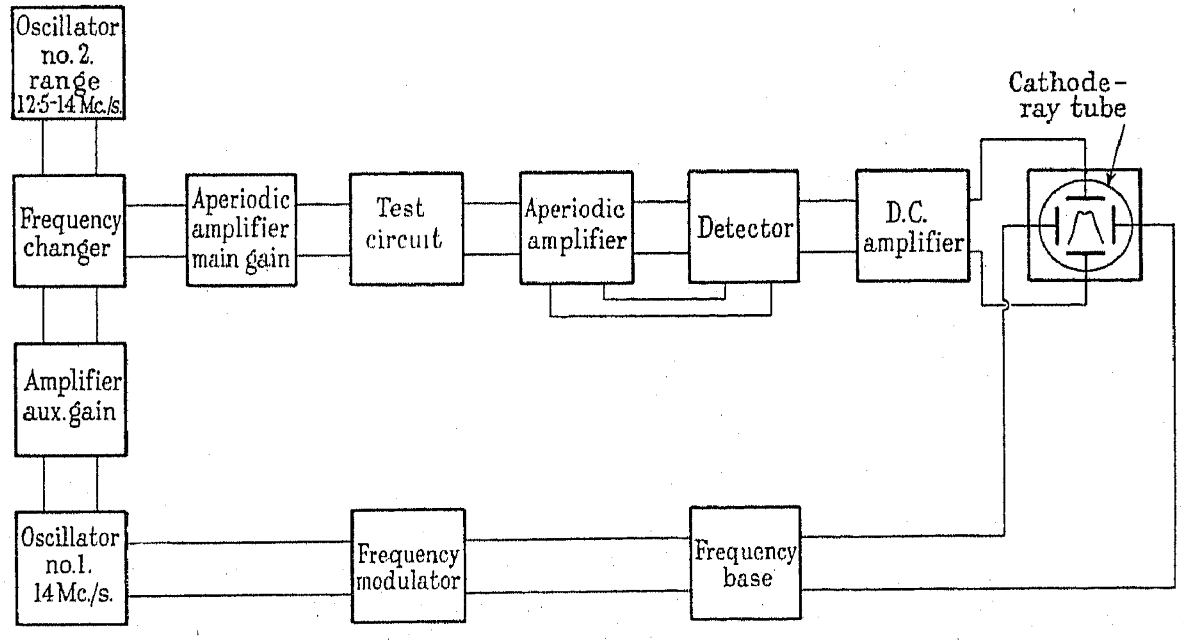

Fig. 1.—Block schematic of apparatus.

The frequency-modulated test voltage is formed from the difference frequency between two oscillators operating at about 14 Mc./s. This system has three advantages: it simplifies frequency-modulation problems, reduces the possibility of amplitude modulation, and also allows the test frequency range, 50 to 1 500 kc./s., to be covered by one tuning capacitance.

Frequency modulation linearly proportional to the frequency base voltage is obtained by a variable-reactance valve, the gain of which is controlled by the frequency base voltage. The variable-reactance valve is connected across the tuned circuit of oscillator 1, which has a mid-frequency of 14 Mc./s., frequency modulation of ± 50, 20, 10 and 5 kc./s. being achieved by a four-stepped adjustment of the frequency base voltage supplied to the variable-reactance valve. A buffer amplifier valve with an anode circuit having a flat frequency response from 14·05 to 13·95 Mc./s. is inserted between oscillator 1 and the signal grid circuit of the triode-hexode frequency-changer valve. The buffer amplifier is of the variable-mu type, and auxiliary gain control of the test frequency amplitude is obtained by control of its grid-bias voltage. The triode portion of the frequency changer is used as the second oscillator, and has a range from 12·5 to 14 Mc./s. The difference frequency is thus capable of variation over the required test range of 50 to 1 500 kc./s., and the anode circuit of the frequency-changer valve has a flat frequency response over that range. A variable-gain amplifier valve is inserted between the frequency changer and the test circuit. The latter is followed by an amplifier having a flat frequency response from 50 to 1 500 kc./s., and two detectors supplying a push-pull d.c. amplifier, the output from which is connected to the two Y plates of the cathode-ray tube. The selectivity curve is drawn on the cathode-ray tube screen, the curve repeating itself at the frequency of the saw-tooth voltage supplying the frequency base. The equipment is transportable, as will be seen from Fig. 2.

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† Marconi School of Wireless Communication.

‡ Automatic gain control.

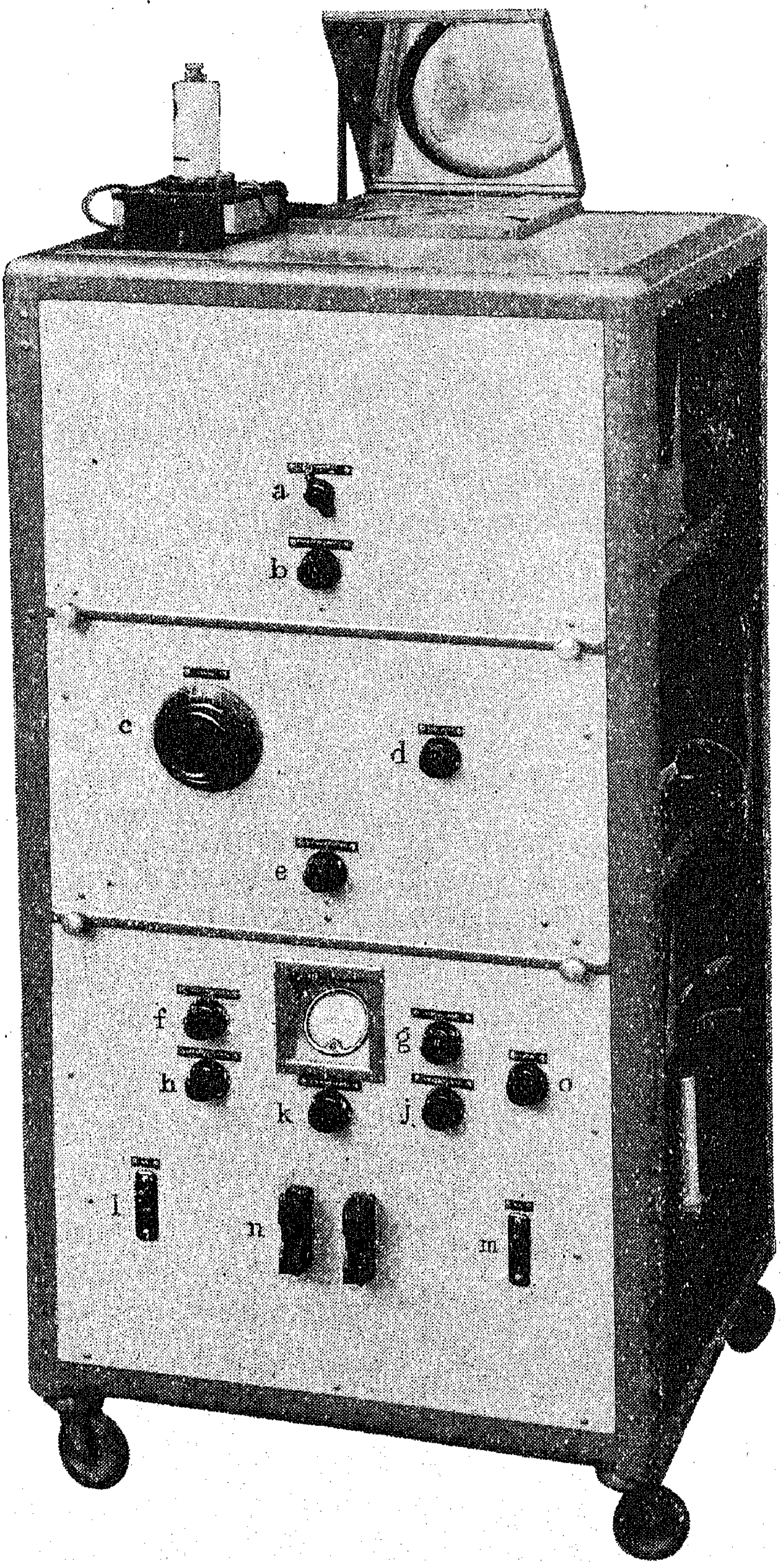

Fig. 2.—Outside view of the apparatus.

a.—Test circuit H.T. switch.
b.—Main gain control.
c.—Tuning.
d.—Band width.
e.—Auxiliary gain control.
f.—Sweep frequency.
g.—Vertical shift.
h.—Sweep amplitude.
j.—Horizontal shift.
k.—Cathode-ray tube heater.
l.—A.C. switch.
m.—H.T. switch.
n.—Fuses.
o.—Focus.

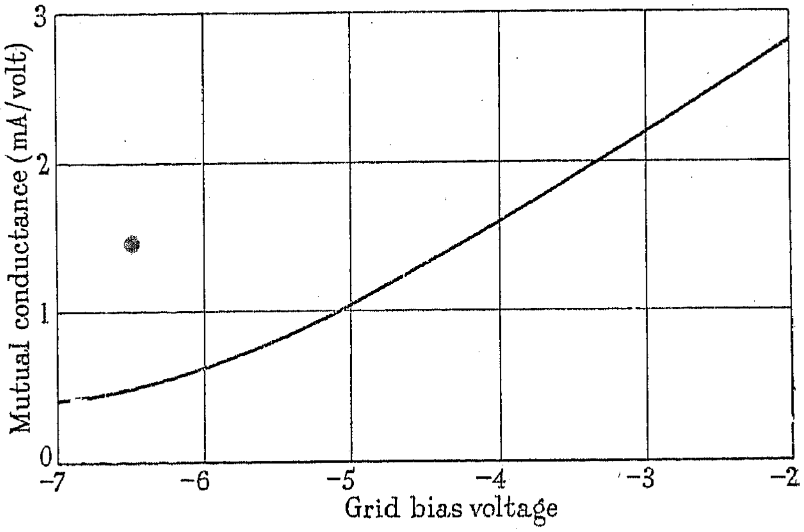

Fig. 3.—Mutual-conductance/bias-voltage curve for V.M.P.4.G valve.

E_A = 250 volts. E_s = 100 volts.

LOGARITHMIC INPUT-OUTPUT RELATIONSHIP FOR THE DECIBEL DELINEATION OF FREQUENCY RESPONSE

Three methods of logarithmic control were tried. A super-regenerative detector was first used as suggested by Bagno and Posner,* but this method was rejected as unsatisfactory because stable operation and a large logarithmic range could not be obtained. In a second method an attempt was made to obtain the logarithmic control by employing variable-mu valves in the d.c. amplifier after the detector, but a range of only 20 db. could be obtained.

The third method, finally adopted, employed an automatic-gain-control amplifier. It was suggested by examination of the input-output curve of a receiver fitted with automatic gain control. This curve appeared to have a logarithmic relationship over a certain range of input voltage, so that it seemed probable that the required logarithmic characteristic could be obtained by using the output voltage from the detector to control the gain of the amplifier between it and the test circuit. The possibility of using this method was explored theoretically for a Marconi V.M.P.4.G valve. Let us suppose that the following conditions apply to a typical A.G.C. circuit (see Fig. 4):—

---

* "A Logarithmic Cathode-Ray Resonance-Curve Indicator," *Radio Engineering*, 1936, **16**, p. 15.

Initial bias of V.M.P.4.G .. .. = − 2 volts
Detection efficiency of A.G.C. diode = 0·85
Impedance in anode circuit of V.M.P.4.G .. .. = 3 000 ohms

The low value of 3 000 ohms is necessary to obtain aperiodic amplification over the test frequency range of 50 to 1 500 kc./s. Taking the $g_m E_g$ curve of Fig. 3 as typical of the V.M.P.4.G valve, we may calculate the input-output A.G.C. characteristic. For example, if the total bias applied to the valve is − 3 volts, and the initial bias of − 2 volts is assumed unchanged:—

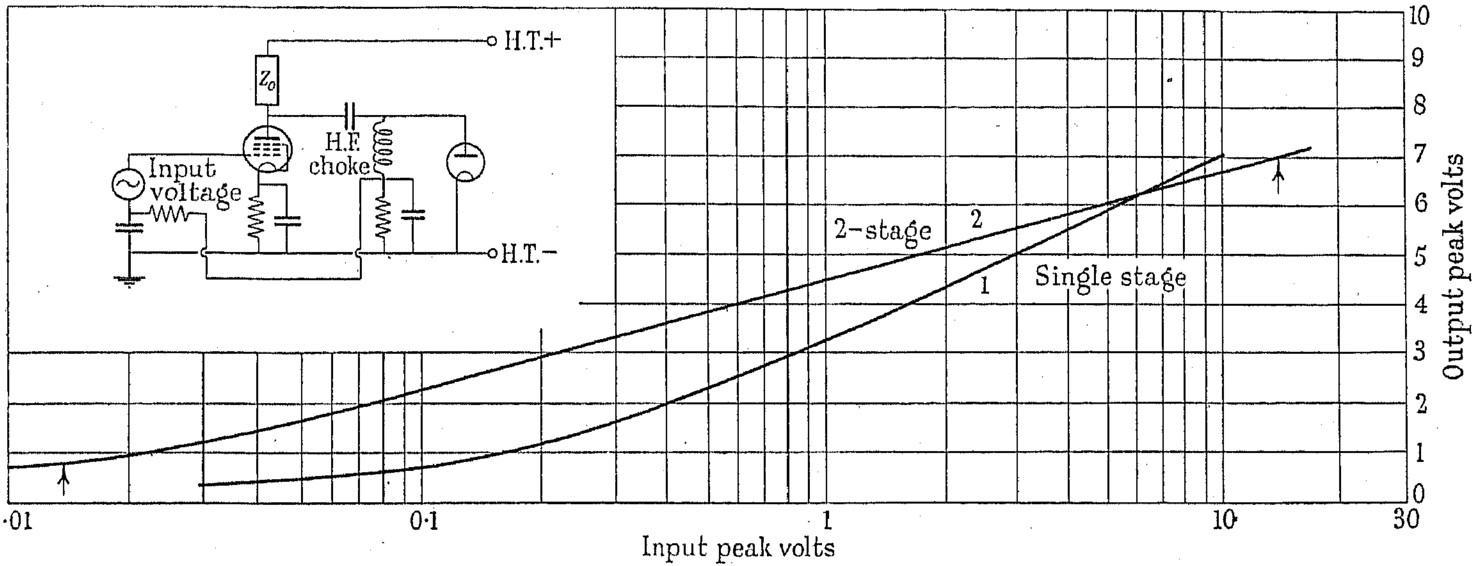

Fig. 4.—Input/output voltage curves for A.G.C. amplifier with V.M.P.4.G valves.
Arrows mark the 60-db. limits.

A.G.C. bias = − 1 volt.

Peak output voltage

$$= \frac{\text{A.G.C. bias}}{\text{Detection efficiency}} = \frac{1}{0\cdot 85} = 1\cdot 175$$

g_m at − 3 volts bias = 2·2 mA/volt

Input peak voltage

$$= \frac{\text{output}}{g_m Z_0} = \frac{1\cdot 175}{\dfrac{2\cdot 2 \times 3\,000}{1\,000}} = 0\cdot 178 \text{ volt}$$

Other points may be similarly obtained, and the result is curve 1 in Fig. 4. Curve 2 shows the input/output characteristic for a two-valve A.G.C. amplifier. This curve indicates that a uniform decibel scale can be obtained over a range of 60 db. The term "uniform decibel scale" implies that the output voltage is directly proportional to the logarithm of the input voltage, or $E_0 = K \log E_1$. There are, however, limitations to the output and input variations. The characteristics of the detector determine the permissible variation in output voltage, since the latter must give a d.c. output linearly proportional to the applied r.f. voltage. The most suitable type of detector is a diode, with which only the minimum permissible r.f. output is limited; a normal value above which detection may be expected to be linear is 0·5 V. The 60 db. variation of input voltage for the two controlled V.M.P.4.G valves gives an output variation from 0·8 to 7 volts, values within the capability of a diode detector. The input voltage maximum (14 V) to the A.G.C. amplifier is, however, excessive because, apart from considerations of distortion, the input voltage cannot be allowed to exceed the bias voltage, since grid current must not occur. This defect may be overcome by inserting a fixed-gain amplifier between the A.G.C. amplifier and the detector. The input-output voltage uniform decibel relationship is in no way affected, but the voltage required at the input of the A.G.C. amplifier is reduced to $1/A$ of its original value, where A is the amplification of the fixed-gain stage. For example, the maximum input voltage required for the two-valve A.G.C. amplifier is reduced from 14 volts to 1 volt if the amplification of the fixed-gain stage is 14, and a maximum input voltage of 1 volt should produce negligible distortion in the A.G.C. amplifier.

It is clear, therefore, that a 60-db. range may be expected from an A.G.C. amplifier having two controlled V.M.P.4.G valves and a fixed-gain valve between them and the detector. The A.G.C. voltage wave-shape applied to the controlled valves must be that of the r.f. modulation envelope, the shape of which is the frequency response of the test circuit regularly repeated at the frequency of the frequency base voltage. The A.G.C. filter therefore needs careful design in order to prevent feedback of r.f. voltage and yet to pass with little attenuation or phase change the l.f. components of the frequency-response wave-shape.

THE A.G.C. AMPLIFIER AND DETECTOR GIVING A LOGARITHMIC INPUT-OUTPUT RELATIONSHIP

A diagram of the A.G.C. amplifier and detector circuit is given in Fig. 5; the amplifier valve preceding the test circuit is also shown.

The test circuit input is connected to the anode of the amplifier valve V1 and H.T. +, and the output to the grid of the first valve (V2) of the A.G.C. amplifier and the A.G.C. line. Two V.M.P.4.G valves are used in the A.G.C. stages, and an N.43 valve for the fixed gain valve before the detectors. Self-bias is used on all three valves, although this results in a reduction of standing bias on the V.M.P.4.G stages as A.G.C. bias is applied. The theoretical decibel curves of Fig. 4 were obtained assuming a fixed standing bias, but no departure from linearity due to this difference was observed experimentally. The anode circuits of the V.M.P.4.G and N.43 stages, which are aperiodic over the range 50 to 1 500 kc./s., consist of a resistance and inductance in series. Resistances are included close to the anode and grid pins of the N.43 valve to prevent parasitic oscillation. Two diode detector valves are used in order to provide the push-pull d.c. voltage to the d.c. amplifier. Push-pull operation has the advantage of doubling the deflection on the cathode-ray tube for a given output from the N.43 valve as well as removing trapesium distortion. It is important to note that both diodes detect the negative envelope of the r.f. output voltage modulated by the frequency-response wave-shape. Detection of the positive envelope by one diode and the negative by the other gives unequal output voltages when the r.f. output voltage exceeds a certain value within the required 60 db. range. This was traced to distortion in the preceding amplifier valves due to curvature of their I_aE_g characteristics. This curvature caused greater amplification of the positive modulation envelope. The variation between the positive and negative envelopes was negligible for high test frequencies (1 000 to 1 500 kc./s.) but appreciable for low frequencies (50 to 500 kc./s.). This difference was caused by the amplifier characteristic which attenuates the r.f. harmonics of the higher test frequencies. The effect was considerably reduced by lowering the screen voltage of the second V.M.P.4.G valve, as distortion from this valve is in opposition to that produced in the first V.M.P.4.G and the N.43 valves, and can be used to cancel the overall distortion. The screen voltage of the first valve was made 110 and that of the second 75 volts.

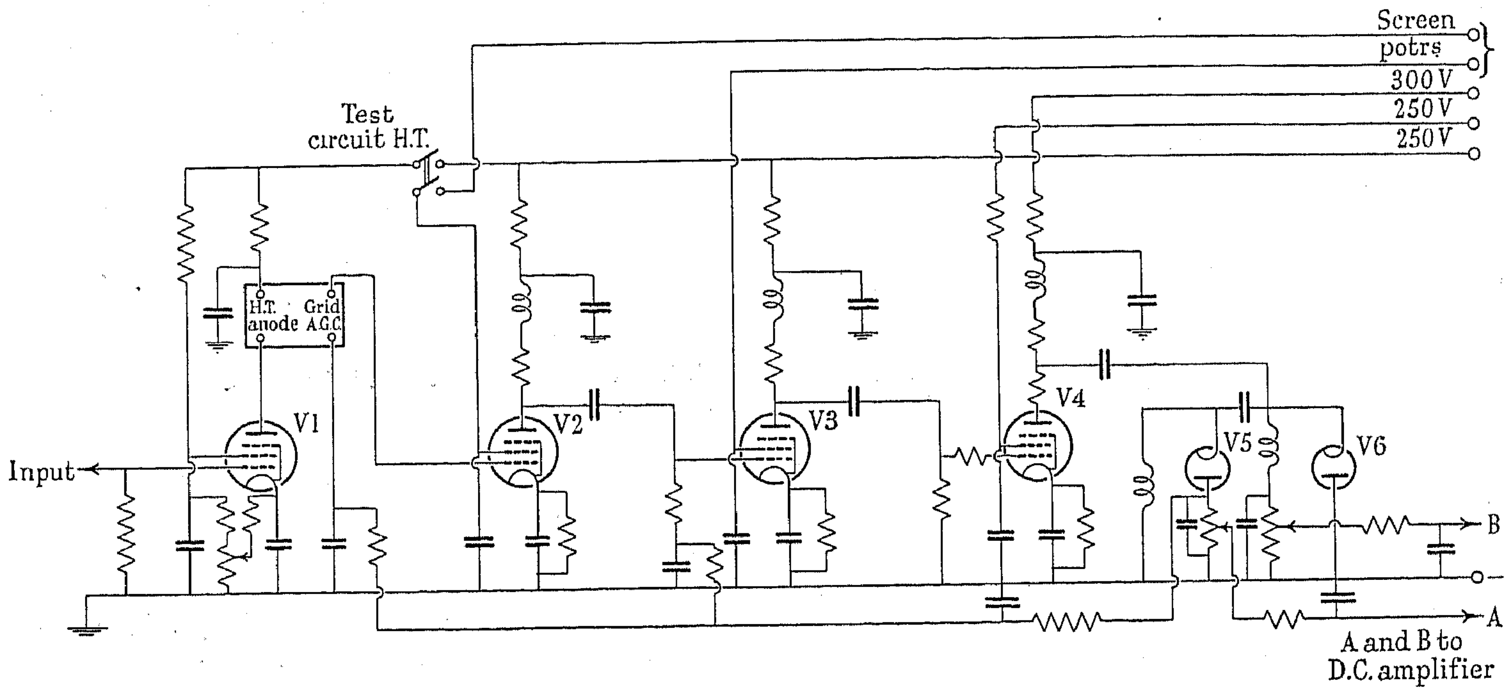

Fig. 5.—A.G.C. amplifier and detectors.

Complete equality of positive and negative envelope over the frequency range was still not obtained, so that it was decided to use the negative envelope only. Final check tests on the decibel scale over the complete test frequency range show no anomalies when negative envelope detection is employed. No visual hum due to the "floating" position of the detector cathodes is observed.

The overall frequency response of the A.G.C. amplifier is shown in Fig. 6 over the range 50 to 1 500 kc./s. Frequencies below 50 kc./s. are attenuated by using low values of interstage coupling capacitance. This is necessary to prevent "motor-boating" and amplification of the l.f. components of the A.G.C. voltage. Two curves are given in Fig. 6; the full curve was taken without A.G.C. bias and the dotted curve with A.G.C. The procedure adopted in both cases was the same, viz. the input voltage was varied to maintain a constant current in the A.G.C. diode (40 μA). The dotted curve shows that there is some positive feedback along the A.G.C. line at low test frequencies. The error introduced in a frequency-response curve at any test frequency between 100 and 1 500 kc./s. is not greater than ± 0·5 db. for the maximum frequency modulation ± 50 kc./s.

The method of connecting the A.G.C. and the phase-changing diodes to the N.43 valve should be noted. The phase-changing diode V6 is connected first to the N.43 anode through 0·0001 μF, and the A.G.C. diode V5 is connected to V6 by a 0·001-μF capacitance. This was done to eliminate an irregularity in the frequency response of the second diode circuit due to parallel resonance (550 kc./s.) between the first section of the r.f. choke and its self-capacitance. By allowing this resonance to be passed back to the A.G.C. diode it was smoothed out.

The A.G.C. voltage is obtained from the diode (V5) load resistance, the detected voltage across which is negative with respect to earth. The A.G.C. filter must, while attenuating all r.f. voltages, allow all l.f. components of the modulation envelope to be passed without serious attenuation or phase change. The load resistance of the diode is limited to 100 000 ohms because of the necessarily large effective parallel capacitance, which, owing to the low filter resistance value, includes the filter capacitance. Non-tracking of the detector, producing amplitude distortion of the modulation envelope, results if X_c/R is less than M,* where X_c is the l.f. reactance of the capacitance in parallel with R, the diode d.c. load resistance, and M the modulation ratio.

The total shunt capacitance in the circuit is $0 \cdot 005\ \mu$F, so that, if $M = 1$, $X_c = R$, giving $f = 325$ c./s. as the highest modulation frequency detected without distortion. This limits the permissible repetition frequency of the response curve because many harmonics of the repetition frequency must be present to reproduce the response curve wave-shape accurately. If the repetition frequency is 25 c./s., harmonics up to the 13th are detected without distortion, a frequency which appears to be adequate except with very sharp-sided response curves. Reduction of the repetition frequency below 25 c./s. leads to better delineation of sharp-sided curves due to the distortionless detection of more harmonics, and also reduces the possibility of producing damped forced oscillations on the side of the curve due to shock excitation of the filter by the frequency modulation. Flicker, however, is then very objectionable and 25 c./s. is chosen as representing a suitable compromise in most cases.

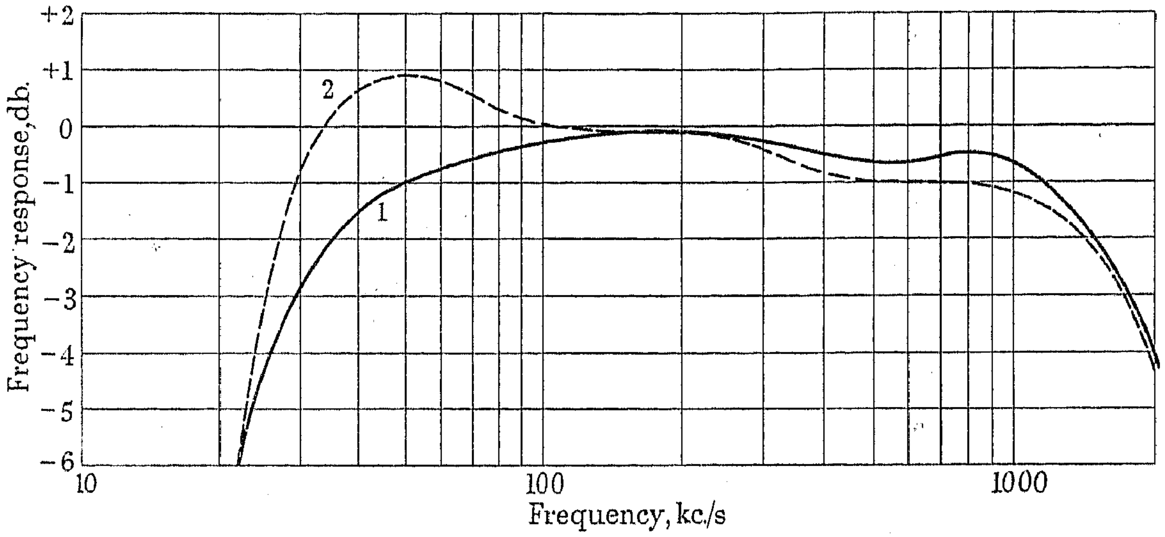

Fig. 6.—Frequency response of the A.G.C. amplifier.
Curve 1. Without A.G.C.
Curve 2. With A.G.C.

The 25-c./s. frequency base is locked with the 50-c./s. mains supply so that all measurements are taken at the same repetition frequency. Synchronization has the additional advantage of increasing picture steadiness.

The r.f. filters between the diode d.c. load resistance and the controlled stages are chosen to give minimum l.f. filtering consistent with stability.

In order to reduce the shunt capacitance across the detector load resistance and yet retain a fixed time-constant, high values of resistance and low values of capacitance are preferable. A minimum limit to capacitance is found necessary to prevent instability, and this requires the resistance values to be much less than the detector load resistance (about 1/10th).

THE D.C. PUSH-PULL AMPLIFIER

A d.c. amplifier is used after the detectors for two reasons, viz.:—

(1) The decibel scale can be calibrated by means of unmodulated r.f. voltages from a signal generator having a calibrated attenuator.

(2) The datum line is fixed. With a.c. amplification the frequency response curve is disposed above and below a centre line which has a variable relationship to the datum line. The datum line is only of importance because the uniform decibel scale has a limited range (60 db.). In these circumstances a.c. amplification requires a sliding scale, the exact position of which necessitates a knowledge of the r.f. voltages applied to the detectors.

THE CATHODE-RAY TUBE

A gas-focused cathode-ray tube having a separate power supply is employed because of its high deflection sensitivity. Owing to the d.c. amplification the vertical deflector plates are not at earth potential, and to avoid spot defocusing the average d.c. voltage between the plates and the anode is reduced to zero by connecting the latter to a potentiometer across the h.t. supply to the d.c. amplifier. Origin distortion is eliminated by suitably biasing the deflector plates. On the frequency base it is corrected by biasing the deflector plates by an amount slightly greater than the peak value of the frequency base voltage. This deflects the trace to one side of the screen, and a magnetic field is used to return it to the central position.

Origin distortion on the response scale is avoided by adjusting the bias of the push-pull d.c. amplifier valves to give an initial voltage difference between the two anodes, and therefore between the deflector plates, of 10 volts. The valve having the higher anode voltage is operated from the diode which gives increasing negative bias with increase of signal, whereas the valve with lower anode voltage is operated from the diode giving increasing positive bias. Hence the voltage difference between the deflector plates increases with increasing signal voltage. Correct positioning of the datum line at the bottom of the screen is obtained by magnetic deflection.

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* F. E. Terman: Discussion on paper by J. R. Nelson entitled "Some Notes on Grid Circuit and Diode Rectification," *Proceedings of the Institute of Radio Engineers*, 1932, **20**, 1971.

The correcting fields are produced by two pairs of coils mounted accurately at right-angles round the neck of the cathode-ray tube.

CALIBRATION OF THE SELECTIVITY METER

The calibration of the decibel and frequency scales is limited to the 8- and 10-cm. sides respectively of a rectangle, as this is the maximum area of screen which can be used without encountering distortion due to fringing of the correcting magnetic field.

THE FREQUENCY SCALE

Oscillator No. 2 (Fig. 1) was calibrated in terms of the mid-frequency by beating the difference frequency, unmodulated by the frequency base, against a standard oscillator. The frequency scale, which for each of the modulation ranges gave deflections linearly proportional to frequency, was also calibrated against a standard oscillator.

THE DECIBEL SCALE

The calibration of the decibel scale was carried out with an aperiodic test circuit giving a horizontal line selectivity curve. A Marconi-Ekco signal generator replaced the test frequency input to the amplifier before the test circuit. The datum was set with no signal to the 0 cm. position on the 8 by 10 cm. rectangle on the screen. The input signal from the generator was increased until 80 μA was registered in the A.G.C. diode; this represents maximum undistorted output from the A.G.C. amplifier. The control potentiometers (see outputs A and B in Fig. 5) were set to give approximately equal output voltages from the d.c. amplifier valves and to bring the aperiodic selectivity line to a position 8 cm. from the datum line. The input voltage was then decreased in 5-db. steps and the distance from the datum line noted. The calibration curve is given in Fig. 7. From 0·8 cm. to 8 cm. the decibel scale is uniform, giving a range of 60 db. A range of 70 db. is possible if the curved part of the scale is used.

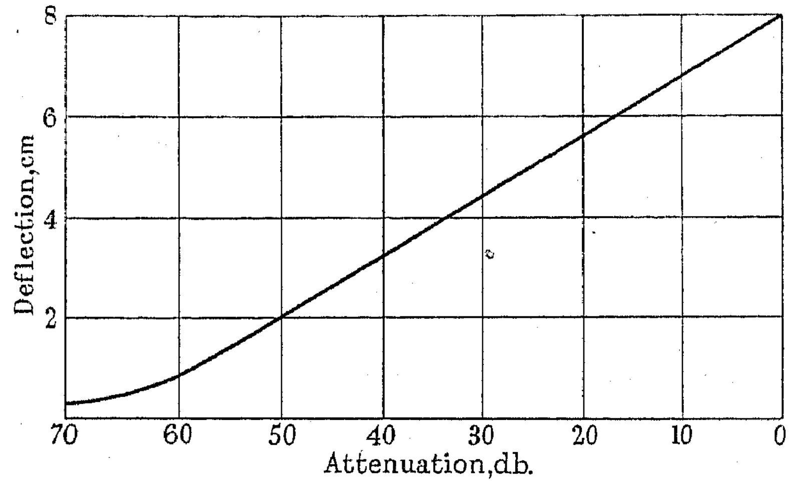

Fig. 7.—Decibel scale calibration.

CHECK TESTS ON THE DECIBEL SCALE

The decibel scale was checked at three frequencies, 1 500, 500 and 100 kc./s. For the first two frequencies the test circuit was an aerial transformer, the untuned primary winding being connected to the anode circuit of the test frequency amplifier and the tuned secondary to the A.G.C. amplifier. The gain of the former amplifier was adjusted to set the peak consecutively at 8, 7, 6, etc., centimetres from the datum line. The curve shape above the 1-cm. line remained unaffected by its position on the scale, thus showing that the decibel delineation held over the specified range. The selectivity was also measured independently at 500 kc./s., using the calibrating signal generator, an amplifier valve, the aerial transformer, and a valve voltmeter across the secondary of the latter. The valve voltmeter reading was maintained constant at 0·5 (peak) volt, and the signal generator attenuator setting noted at different frequencies. The results of this test are tabulated below, together with those obtained by the selectivity meter.

Frequency kc./s.	Direct	Selectivity meter
450	40	39·5
460	35·8	35·5
470	31·2	31
480	25·8	26
490	16·5	16·5
495	8·7	8·5
500	0	0
505	9	9
510	18·7	18·5
520	27·8	27·5
530	34·1	34
540	39·3	39
550	44·0	43·5

The agreement between the two methods is good and it is clear that the accuracy of the instrument depends mainly on the accuracy of the original calibrating instrument (the signal generator).

Finally a test on an intermediate-frequency transformer with double-humped frequency response proved that the decibel delineation was satisfactory at 100 kc./s.

Sources of possible error are damping of the test circuit by the anode resistance of valve V1 (Fig. 5) and by variation of input impedance of the A.G.C. amplifier due to space charge and grid-anode capacitance. The former effect is overcome by limiting the minimum bias on the valve to give an anode resistance much higher than would damp any normal test circuit. The latter effect is very small and is only noticeable for low A.G.C. bias voltages, i.e. small input signals, and is therefore confined to the part below the 60-db. level on the decibel scale.

Acknowledgment

Grateful acknowledgment is made by the authors to Marconi's Wireless Telegraph Company for permission to publish the description of the apparatus.

A CRITICAL SURVEY OF AMERICAN METERING PRACTICE

By G. F. SHOTTER, Member.*

(*Paper first received* 16*th February, and in revised form* 13*th March*, 1939; *read before the* METER AND INSTRUMENT SECTION 14*th April*, 1939, *and before the* NORTH MIDLAND CENTRE 30*th March*, 1940.)

SUMMARY

The first part of the paper gives a general survey of the conditions at present existing in America in regard to metering, and describes some meter departments and their methods. The Regulations governing metering practice issued by some of the American State Commissions are then discussed, and comparisons are made with the Regulations issued by our Electricity Commissioners. As a standard of comparison, the New York State Commission Regulations are dealt with in some detail, and it is shown that they are more comprehensive than our own.

Methods of testing and servicing are also described and brief notes are given on records and costs. The trend of metering developments, particularly with regard to standardized meters and outdoor metering, is dealt with, and the paper concludes with notes on subjects of general metering interest.

INTRODUCTION

This survey is based on a recent visit to the United States of America by the author, who investigated American metering practice on behalf of his company. The following supply utility companies were visited:—The Consolidated Edison Company, New York; The Public Service Electric and Gas Company, New Jersey; The Detroit Edison Company, Detroit; The Commonwealth Edison Company, Chicago; and the Public Service Company, Northern Illinois. Two manufacturing companies were also visited, these being the Sangamo Electric Company, Springfield, and the Westinghouse Electric and Manufacturing Company, Newark, New Jersey.

Before dealing with American metering practice in detail, the author feels that a few general impressions will assist him to present the subject in its proper perspective.

The utilities which he visited are acknowledged to be among the best in America, and while this paper mainly concerns them he would mention that he was fortunate in being able to obtain a good idea of the general conditions in most parts of the country.

STANDARD OF ACCURACY, AND METERING PRACTICE

The author is of the opinion that there is very little to choose between the best meter departments in England and America as regards the standard of accuracy which they maintain and their metering practice.

He obtained the impression, however, that the average level of accuracy and metering practice in America is at present higher than the general level in this country. It is evident that the Americans have had, and still have, a real appreciation of the necessity for maintaining a high standard of accuracy.

State Regulations governing the metering practice of all the various utility companies have been in force for some years in America, covering not only initial testing but also periodic testing and servicing; for instance, one set of Regulations was published in 1920.

While legal limits of accuracy have existed for many years in this country, it must be admitted that the general standard of accuracy maintained by our supply authorities and companies taken as a whole has varied considerably.

No doubt the general standard of testing will be raised when the full effect of the Electricity Supply (Meters) Act, 1936, is felt, but it is the author's view that the existing regulations will have to be amplified before a high standard of accuracy can be properly maintained. He refers particularly to the periodic return of meters for servicing and retesting. It will be appreciated that if a meter can remain in service without retest and overhaul for an indefinite period, any regulations as to its accuracy at the time of installation become ineffective from the point of view of a general standard of accuracy. The Americans appear to be ahead of us in this respect. It should be borne in mind, of course, that several companies in this country have for many years returned their meters from service on a definite time schedule.

THE AMERICAN REGULATIONS

Each State in America has its own Electricity Commission, there being no main or Federal Commission which would be the equivalent of the Electricity Commission of England. Those controlling the electric utilities which the author visited were as follows:—

New York State Commission, controlling
    The Consolidated Edison Co., New York.

New Jersey State Commission, controlling
    The Public Service Electric and Gas Co., New Jersey.

Michigan Public Utilities Commission, controlling
    The Detroit Edison Co., Detroit.

Illinois State Commerce Commission, controlling
    The Commonwealth Edison Co., Chicago.
    The Public Service Co., of Northern Illinois.

It is proposed to deal later in the paper in some detail with certain of the regulations applied by the above, but it can be stated now that they are in many respects similar to those issued by our Electricity Commissioners.

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* North Metropolitan Electric Power Supply Company.

METER DEPARTMENTS

A feature of all the meter departments which the author visited was that they were well planned. Generally speaking, their equipment is of a high standard and is similar to that of any well-equipped meter department in this country. Obviously the range of testing instruments cannot vary to any great extent, because the problems facing engineers both here and in America are fundamentally the same. It is very apparent, however, that the American meter engineers have not been restricted in their expenditure, because, in addition to being well equipped, their departments are spacious and well lighted. One very fine meter department which has only recently been completed (that of the Detroit Edison Co.) has an area of approximately 25 000 sq. ft. and is designed to give an output of 100 000 meters per annum. Figs. 1–4 (see Plates 1 and 2, between pages 200 and 201) illustrate some of the sections of this department, while Figs. 5 and 6 show the layout of the whole department.

Another typical example of layout is shown in Fig. 7 (see Plate 3), which shows a standardizing bench used by the Consolidated Edison Co., New York. A meter department which is also of interest is that of the Essex Division of the Public Service Electric and Gas Co., New Jersey. This department is one of 11 such departments situated throughout the Company's property and is in the same building as the general testing laboratory consisting of chemical, electrical, mechanical, miscellaneous apparatus and service sections. All the sections are extremely well equipped, the miscellaneous test section having very comprehensive equipment for carrying out " type " tests on every kind of apparatus for the use of consumers.

The author has only mentioned the above departments as examples; those of all the companies which he saw have their individual characteristics.

Before leaving this section, it may be of interest to give the number of meters in service with some of the various utilities which were visited. These were as follows:—

Consolidated Edison Co., New York:—Approximately 3 million.
Public Utilities, New Jersey:—Approximately 1 million.
Commonwealth Edison Co.:—Approximately 1 million.
Public Service Co., N. Illinois:—316 000.

MAKES OF METERS

Meters are manufactured in the United States by only four firms: The Duncan Co., the General Electric Co., the Sangamo Co., and the Westinghouse Co. Friendly co-operation between these firms is most marked, particularly with regard to the interchanging of ideas and patents. The extent of this co-operation is shown by the development of the " plug in " type of meter for outdoor installations. All four makes of meters have identical external dimensions and sizes of sockets and are thus interchangeable. There is no doubt that the American designs of meters were for many years very much better than most British types. The application of precision mass-production methods, and the large number of instruments used, possibly accounted for their advantage in this direction. At the present time, however, the performance of the best British meters would seem to compare very favourably with that of their American counterparts.

All the American manufacturers are extremely keen on research and co-operate not only with each other but with the users. In the author's opinion their developments have been along the right lines, inasmuch as all their meters are amply and well designed and they do not appear to have been affected by any " continental " influence in regard to size.

METHODS OF TESTING AND SERVICING

The main difference between the meter testing in this country and in the United States is that it is a universal practice there to test and service meters on the consumers' premises, whereas practically all our testing and servicing, with the exception of large equipments, is done in the laboratories.

Only new meters are tested in the laboratory in the United States, or alternatively have to be tested on site within a short period of their installation. Laboratory testing also applies to meters returned owing to major faults or for reasons of change of tenancy, demolition, etc. When reinstalled these meters have to be tested again on site.

It is not an easy matter to deal briefly with the relative merits of the methods of servicing and retesting as carried out here and in the United States. It is obvious that servicing on site cannot be carried out so thoroughly as in the meter department workshop, and in this respect the British practice seems to be in advance of the American. By " British practice " the author means servicing in workshops, using thorough methods. To do this it will be appreciated that the meter must be dismantled and certain parts either cleaned or replaced in a detailed manner. This work can hardly be done efficiently on a consumer's premises, because not only does the location of the meter frequently make proper servicing difficult, but it is not possible to carry sufficient equipment to meet all the conditions which can be encountered in overhauling. This criticism was generally admitted by the American engineers.

From many points of view, another disadvantage of servicing and retesting on site is that it brings a large number of employees into direct contact with the consumers.

It will be seen later that the American State Regulations require periodic overhauls and retests of meters at fairly frequent intervals, and thus they possibly feel justified in being less exacting in their methods of servicing than a longer period in service would necessitate.

An important point which must, of course, be borne in mind is that it would not be possible to carry out servicing on site in this country as our Regulations stipulate that a meter ceases to be certified once the seals are broken.

While on the subject of servicing, the extensive use of outdoor metering has led American engineers to investigate very seriously the desirability of servicing and retesting their meters in their workshops and laboratories. Climatic conditions have not only pro-

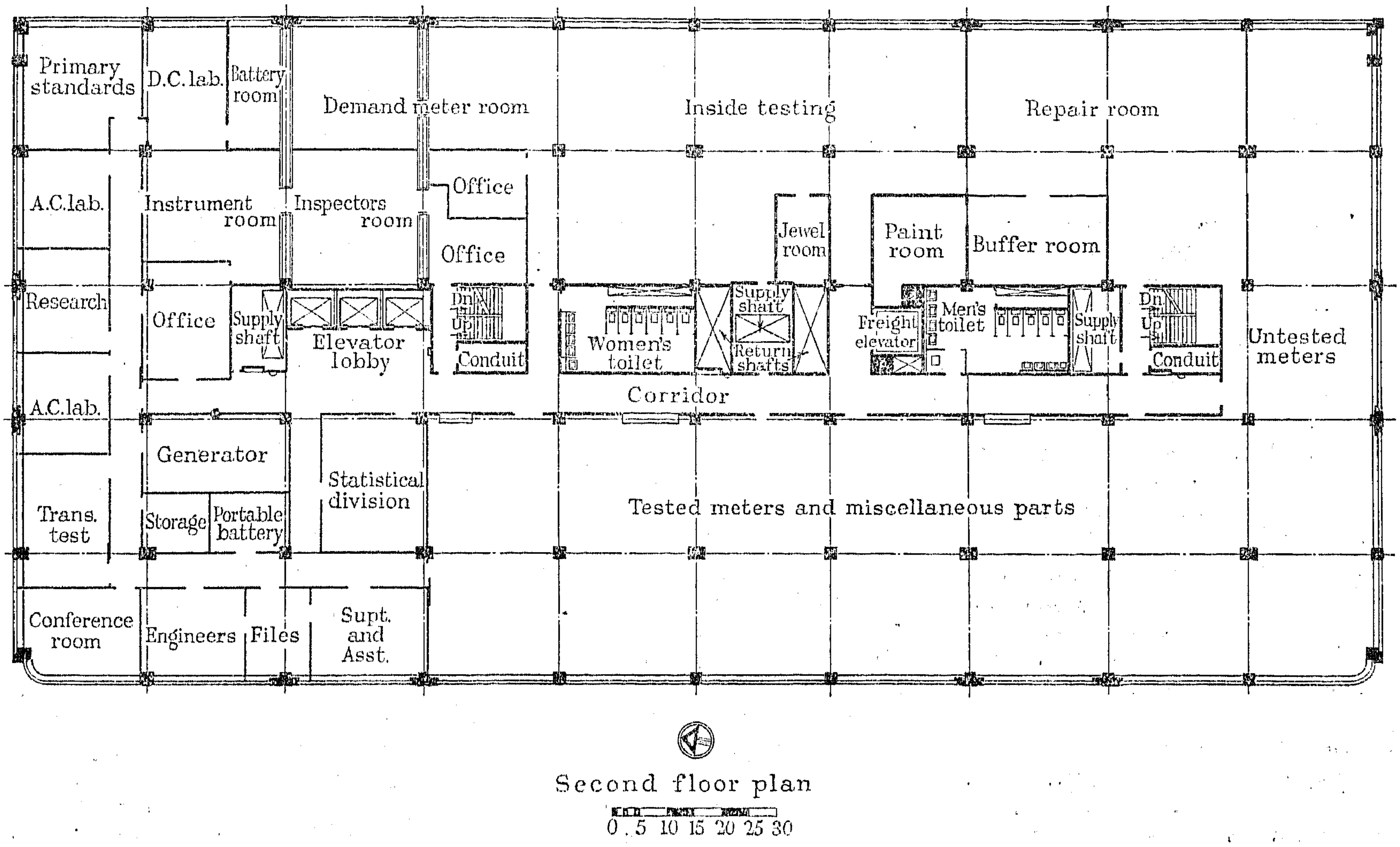

Fig. 5.—Layout of Meter Department, with the several divisions indicated.

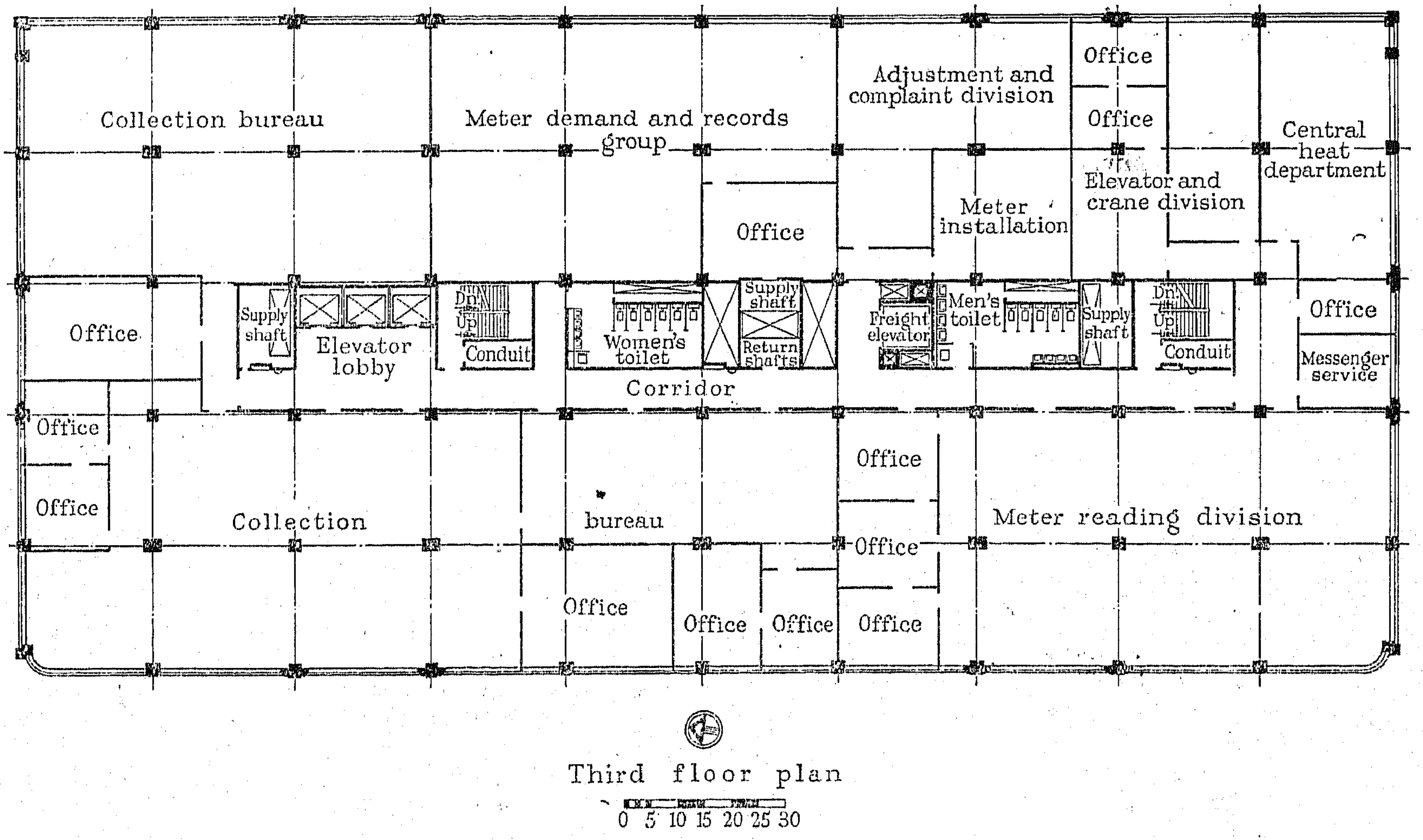

Fig. 6.—Layout of Meter Department Records Division.

duced technical difficulties in connection with bearings, but have also brought about practical disadvantages in regard to servicing, quite apart from the question of whether servicing can be efficiently carried out on site. It is obviously not an easy matter to service a meter at − 40° F.

The main problem which they would have to face in altering their methods is that their routine and records built up over many years would have to be completely changed. The question of servicing costs is another factor.

The author discussed the problem with engineers whom he met, and since his return he has received confirmation that two companies are now actively engaged in the investigation of such a change-over. An article by Mr. F. E. Davis of the Commonwealth and Southern Corporation, Jackson, Michigan,* also throws light on this subject. In favour of the workshop method of servicing, Mr. Davis states that "testing costs are certainly no more, and probably less, than the most efficient field methods yet tried." This article also mentions the use of a motor van equipped with proper test and repair equipment to provide efficient facilities for outdoor servicing. This method has yet to be fully investigated, but it would appear to be particularly useful in rural and scattered areas, which form yet another of their servicing problems.

It must be appreciated, of course, that the Americans have sound reasons for adopting outdoor ironclad installations, one of the main purposes being to thwart consumers who seem to be particularly apt to divert current and disrespect seals.

Outdoor metering has the advantage of making the meter always accessible, and it might be interesting to consider its use in this country, for example in rural areas, under suitable conditions.

ENERGY DIVERSION

One cannot fail to be impressed by the serious difficulties confronting all the American companies in connection with the fraudulent diversion of current and the tampering with meters on the part of consumers. It is estimated that the loss of revenue over the whole country due to these causes is in the region of 5 %. The Public Service Electric and Gas Co., New Jersey, informed the author that they encounter no less than 1 400 cases of fraud per month. They were very astonished to learn that we had such a small number of these in this country and it was rather difficult to convince them of the experience of the author's company in the matter. This excessive diversion in America has been one of the reasons for their adopting the extensive use of ironclad indoor and outdoor meter installations. A document published by the Edison Electric Institute gives the following reasons to account for the huge proportions of this diversion of energy:—

(1) One-third of indoor meter installations employ open wiring.

(2) Overhead service entrance conductors have not been protected.

(3) Seals have not been respected.

It is also interesting to note that the majority of companies have established procedure for dealing with detected cases of diversion without having recourse to law, except in special instances.

This concludes a brief outline of the author's general impressions. Many other aspects of the visit might be mentioned, but the foregoing should give a fairly good general view of the conditions at present existing in America in regard to metering.

COMPARISON OF REGULATIONS

The author now proposes to deal with some of the American Regulations, and as far as possible to draw comparisons with our own. It will be appreciated, of course, that he cannot do more than to comment upon the sections which he considers to be the more important, since most of the documents are very lengthy. With the exception of one, the Regulations of the Commissions under review deal not only with meters but also cover various other subjects, such as "Transactions with Customers," "Service Entrances," "System Operating Requirements," "Earthing," etc.

For the purposes of comparison, the New York State Commission's Regulations seem to be the most interesting from the metering point of view. These are not only the most strict but also the most comprehensive and deal exclusively with meters. It is proposed to deal with this document in some detail, but first some general observations on the various other Regulations may be useful.

The first point which must be appreciated is that two accuracies are stipulated by the American Regulations. These are:—

(1) "As left" accuracy.

(2) "As found" accuracy.

The first applies to tests on meters in the laboratories or to tests *after* adjustment on site. The second applies to service tests on site *before* adjustment, to disputed meters, or to "complaint" or "request" tests as they are commonly called. A brief summary of the two types of accuracy for four Commissions is given in Table 1.

There is, of course, only one legal standard of accuracy in England, the Electricity Commissioners' figures being $+2\frac{1}{2}$ % to $-3\frac{1}{2}$ % at all loads. The Commissioners have intimated, however, that the "as found" tests by the inspector must be within these figures. While on this point, it might be mentioned that the Illinois Commission state that "the allowance of certain variations from correctness is specified to allow for the necessary irregularities in meter tests and maintenance conducted on a commercial scale." They further state that "it is not the intent of the rule that meters may be deliberately set in error by the amount of the tolerance." The author feels that the latter is a wise provision which might have been more definitely stated in the British Regulations. On comparing the figures given by the various American Commissions with our limits, the author is of opinion that when the fact that the American engineers have to test, overhaul, and adjust on site and get their meters within finer limits for their "As left" accuracy is taken into consideration, our tolerances which apply to laboratory tests are somewhat liberal.

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* *Electrical World*, 1938, **110**, p. 1817.

Incidentally, another significant rule from our point of view in the Illinois Commission's Regulations provides that meters up to and including 25 amperes can be tested by the utility or by an approved laboratory of a third party, but that tests by the manufacturers are not acceptable under the Regulations. In the author's opinion, this is a sound rule and is more essential in this country, particularly as meters have not to be tested on site within a short period after being installed.

It will be seen that the New York Commission stipulates that the "as left" accuracy must be from correct to 2 % slow at all loads, whereas the New Jersey Commission allows a tolerance of 1 % fast to 1 % slow at all loads. A high standard of performance is obviously demanded from the utilities operating under these conditions. The effect of the New York State regulations is to penalize the utilities, because, to comply with the accuracy required, they have to set their meters on an average approximately 1 % slow.

It will be observed that the Michigan and Illinois Commissions differentiate between the loads and also give an average error for the " as left " tests.

Referring to the " as found " tests, it will be seen that these are all given as a " calculated average error." The method of calculating this error varies between the different Commissions but, as an illustration, the method employed by the majority of them is to multiply the accuracy obtained at full load by 4, add the result of the test at light load, and divide the result by 5. A similar method embodying 3 test-points is also employed.

At first sight the results obtained from such calculations would appear to be of an ambiguous order, but in practice the author has no doubt that the method is found to be satisfactory. It must be realized, however, that a method of this kind must be employed to find the true average error in certain cases. These are where the meter under test is checked at only a few points on its curve, and where (*a*) it has a fundamentally bad curve and/or (*b*) it has a bad curve due to friction increase or to weakening of the damping magnets. The calculations become further complicated when the meter is operating over a wide range of loads.

The author's view is that matters can be simplified in such cases by the insertion of a suitable check meter having a sensibly straight-line characteristic. A difficulty which can arise in using this method is where the load on the instrument under test is so low that a considerable amount of time must elapse before a sufficiently accurate reading can be taken. In such cases the only alternatives are to use the site-testing method or to return the meter to the laboratory for test. Both methods involve the calculations previously mentioned and a knowledge of the types of load.

One or two other extracts from the various regulations are of interest to illustrate the relations between the consumer and the utilities. For example, the New Jersey Commission has a rule relating to the refund to consumers where the meter has been found to have an average accuracy greater than 4 % fast. The period over which the refund extends is also defined. In the Illinois Regulations it is stated that any adjustment must be based on the actual error of the meter and not on the difference between this and the allowable error.

Table 1

Commission	A.C. Meters	
	Accuracy	
	" As left "	" As found "
New York	Correct to 2 % slow, all loads	± 2 % calculated average error
New Jersey	± 1 % all loads	± 4 % calculated average error
Michigan	± 1 % at heavy load ± 3 % at light load ± 2 % average error	± 4 % calculated average error
Illinois	± 1 % at heavy load ± 3 % at light load ± 2 % average error	± 4 % calculated average error

It is also laid down by some of the Commissions that a meter shall be tested free of charge upon the request of a consumer, if this request is not made more frequently than once in 6 months. This can be compared with the generally accepted practice in this country, where a charge for a request test is only made if the meter is within the legal limits. A consumer can also make application for a test by the Commissioners, for which the New Jersey Commission charges $1.00, but this is refunded by the Commission and charged to the utility if the meter is faster than the prescribed limit outlined above. These charges vary with each Commission. In the case of Illinois the charge depends upon the size of meter, the minimum being $2.00. The Michigan Commission charges $5.00 (minimum) for this test.

Another interesting Regulation of the Illinois Commission relates to the indiscriminate fixing of meters in peculiar situations. This recommends that meters should be installed where possible on the ground floor, near the service entrance, in a clean, dry, safe, place on a stable support free from vibration and not subject to wide variations in temperature. They go on to deprecate the installation of meters " in coal or wood bins " or " in attics, sitting-rooms, bathrooms, bedrooms, restaurant kitchens, over doors, over windows, etc., etc." The author is of the opinion that more importance should be given to the question of suitable installations in this country.

New York Commission Regulations

In view of the Regulations which have been and will be issued by our Commissioners, a more detailed survey of the New York State Commission Regulations as a representative example will possibly provide a very fair standard for comparison.

The author feels that he cannot do better than to quote direct from the Regulations in regard to laboratory requirements.

Standardizing laboratory.

" A standardizing laboratory is a laboratory suitably furnished and equipped to determine the accuracy of meters and instruments used for testing purposes or for the certification of instrument transformers and shunts. No laboratory shall be deemed properly equipped as a standardizing laboratory until it shall have been inspected and received a certificate of approval from the Commission. The certificate of approval shall be effective until abrogated.

The standardizing laboratory equipment shall include:—

A potentiometer of precision type.
Three or more standard cells.
Two sets of standard resistors of suitable ranges to cover working requirements.
One volt box with suitable ranges.
One set of standard resistors and one standard cell shall be held in reserve for reference purposes only and shall be certified once a year by the Bureau of Standards of the Department of Commerce at Washington, D.C., or by other laboratories who maintain standards in agreement with those of the Bureau of Standards."

A special note should be made of the fact that the laboratory must be inspected and have a certificate of approval before it is deemed to be properly equipped. Attention should also be drawn to the number of standard cells required and also to the last paragraph in regard to their certification.

Reference standards.

" For determining the accuracy of portable test standards and of other portable instruments they shall be compared with reference standards, meters and instruments mounted in a permanent position, in a suitable location.

" Reference standards shall be compared, at least once in every three (3) months with the standards of a standardizing laboratory or the standards of the Commission's laboratory. The results of such comparison shall be certified by the proper authority in charge of the standardizing laboratory, and such certificate shall accompany each reference standard."

It should be mentioned here that these instruments are defined by us as substandard instruments, i.e. wattmeters, voltmeters, ammeters, etc. It should also be noted that they have to be tested once in every 3 months. Our regulations stipulate once in every 6 months for similar instruments, and in the author's view this is too long a period between checks. It is further interesting to note that provision is made in this section for the tests to be carried out in an outside standardizing laboratory. This would be a similar condition to that arising in our Class B stations.

Portable test standards.

" All portable test standards used for testing watthour meters shall be compared with reference standards at least once each week for direct-current types, and at least once in every two (2) weeks for alternating-current types, during the time such portable test standards are regularly used. If such comparison shows a portable test standard to be in error by more than one per cent (1 %), plus or minus, at any load at which it will be used, it shall be adjusted and certified by comparison with reference standards.

" Each portable test standard shall be accompanied by a calibration certificate signed by the proper authority in charge of the testing laboratory, giving the date when last certified and the utility's or the manufacturer's number. The certificate may be shown either in per cent accuracy of the portable test standard, or in per cent correction to be applied at the various ampere loads on one or more voltage ranges, or both percentages may be shown. The certificate shall be uniform in size and arrangements of form, and when superseded, shall be filed for a period of six (6) months."

The first point is that the portable test standards are rotating substandard meters or, as the author prefers to call them, working standards. It must also be realized that the American utilities have large numbers of these instruments to enable them to carry out testing on the consumers' premises.

Portable indicating testing instruments have to be checked at least once a week and their error must not exceed 1 % of full-scale deflection. An interesting aspect is that an instrument of this type can have an error exceeding 1 % so long as it is provided with a calibration certificate. In effect this means that the instrument can be used if allowances are made for an error, even though this may exceed 1 %.

Official forms for the calibration certificates for both portable substandards and indicating instruments are not only recommended but also illustrated in the Regulations.

Sections 8–12 of the Regulations define five different types of test on a meter; these are quoted below.

Tests.

" Section (8).—A complaint test is a test of a meter, made by an electric utility, upon the premises where the

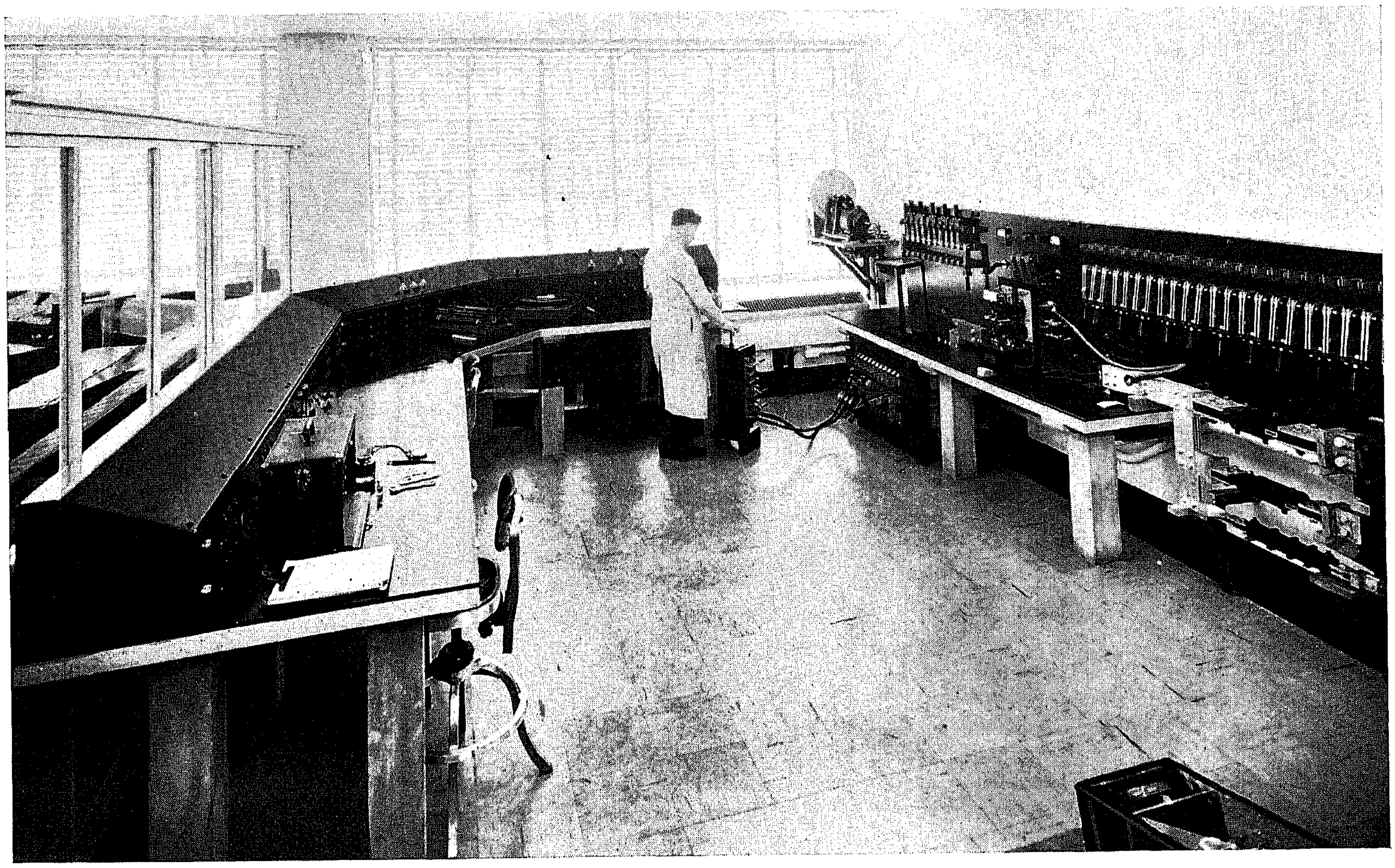


Fig. 1.—General view of the direct-current laboratory of the Standards Laboratory. Storage-battery control panel on the right with heavy copper bus-work and water rheostat. Synchronous timer for controlling test runs, mounted on bracket (right rear). On the left is non-magnetic test table with controls.

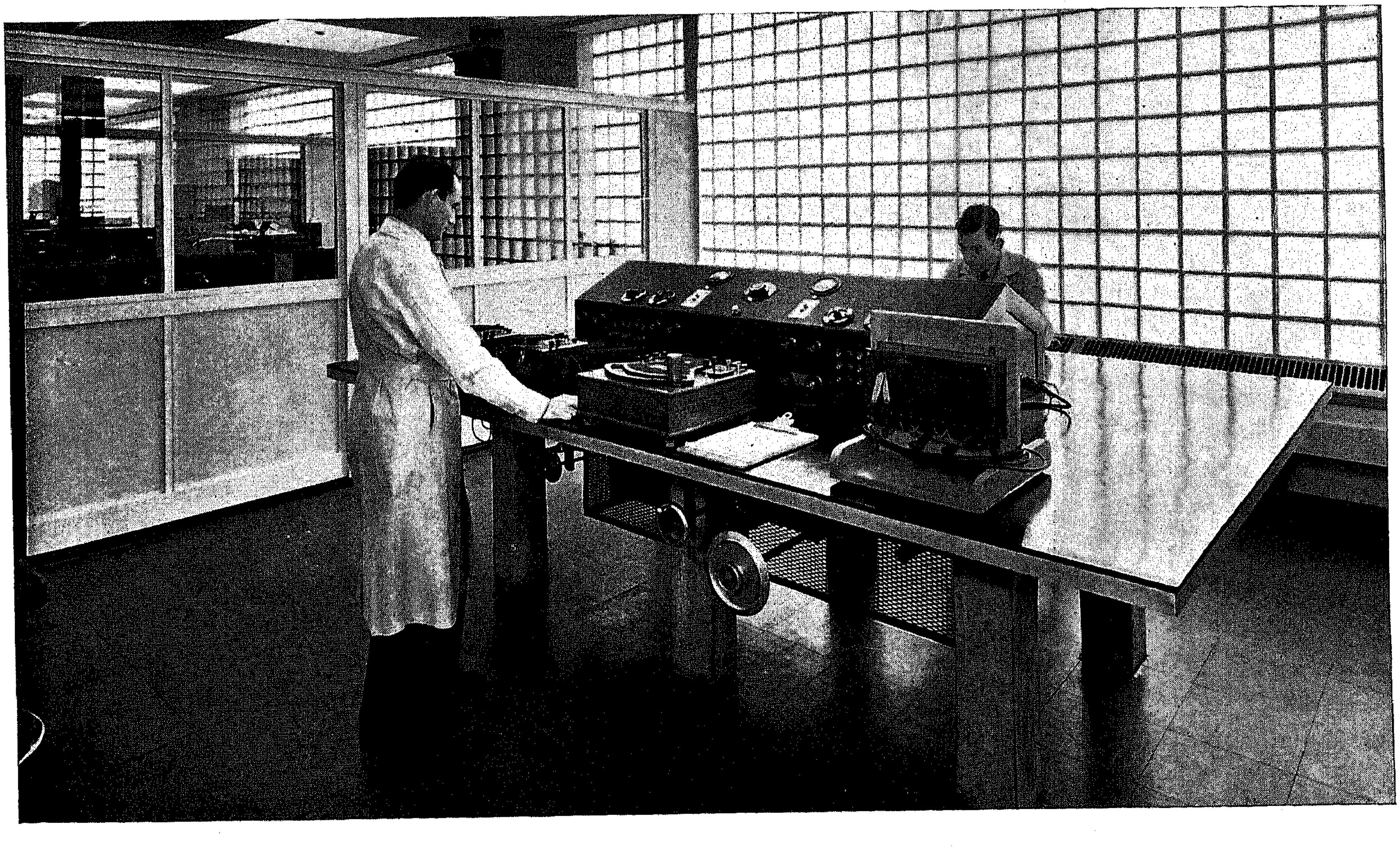


Fig. 2.—Non-magnetic test table with turret-top control panel for general a.c. instrument and test meter testing and calibrating. Note rheostat and phase-shifter controls under table top. Two of these rooms are part of the Standards Laboratory.

Plate 2

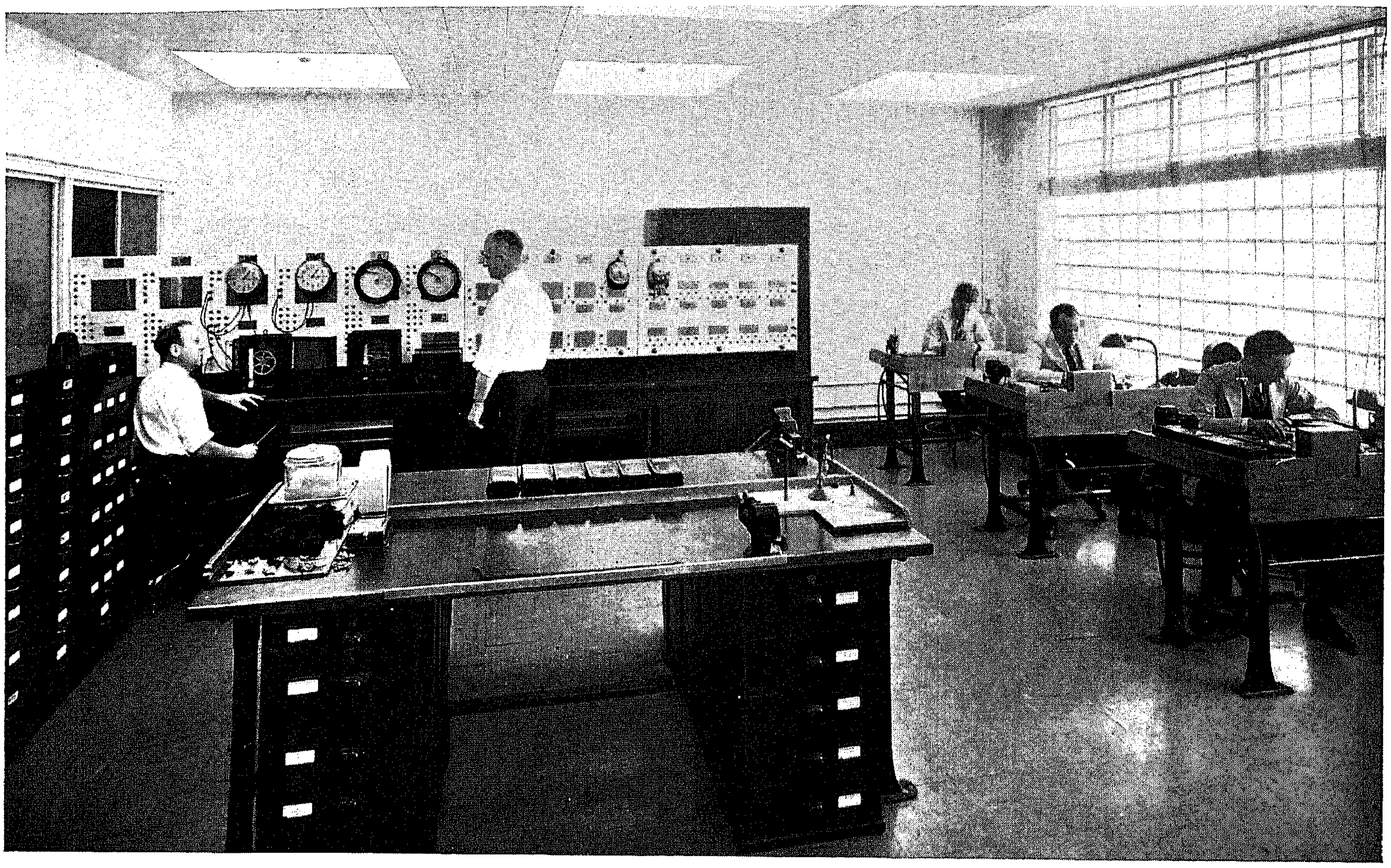


Fig. 3.—General view of the demand meter repair benches and test tables, with special parts cabinets on the left.

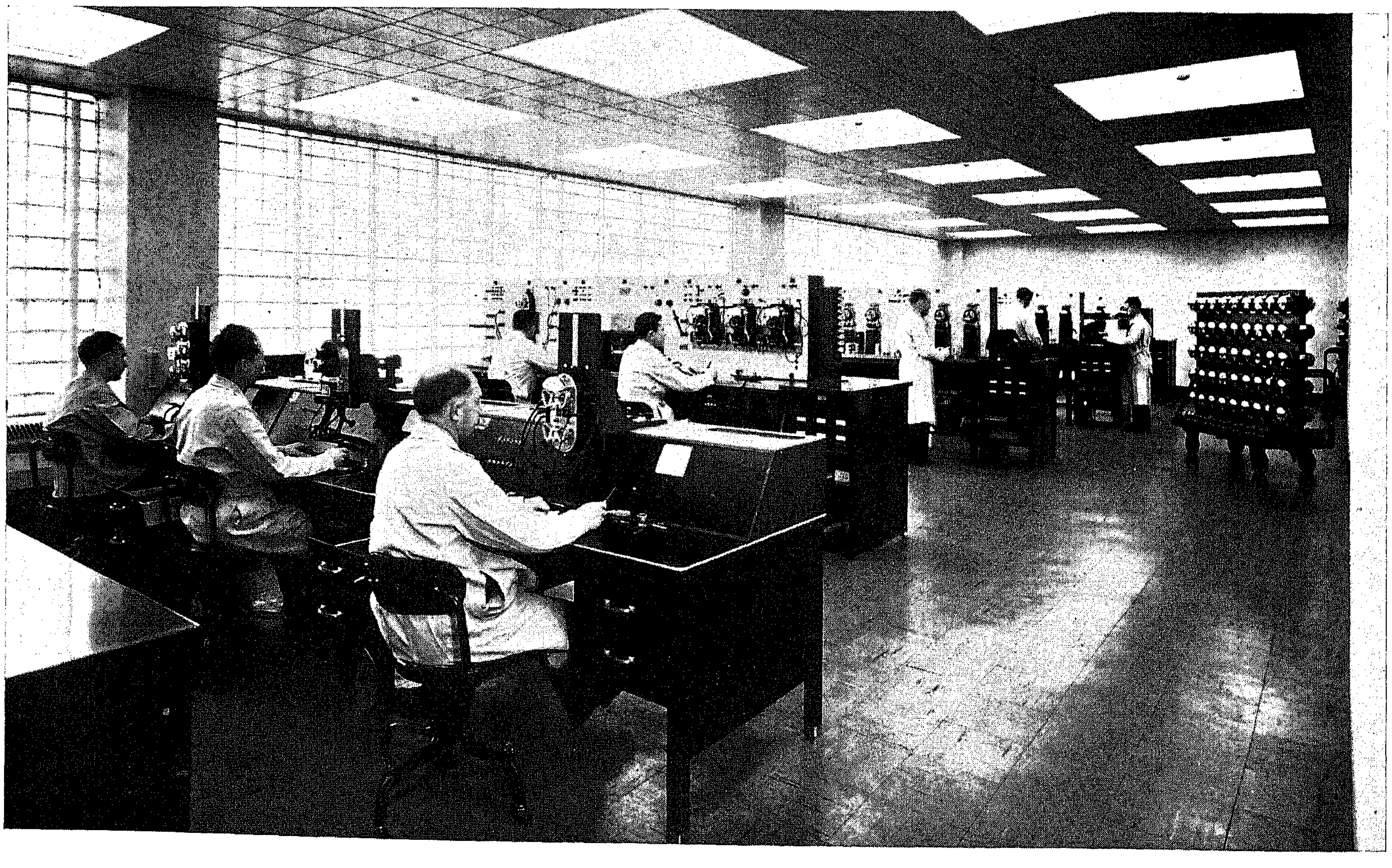


Fig. 4.—General view of part of the Shop Testing Division. In the foreground are 3 new-type polyphase meter test tables, immediately behind which is the general d.c. meter test table. In the rear are shown three 9-position single-phase gang test tables with parts cabinets on the ends of the tables.

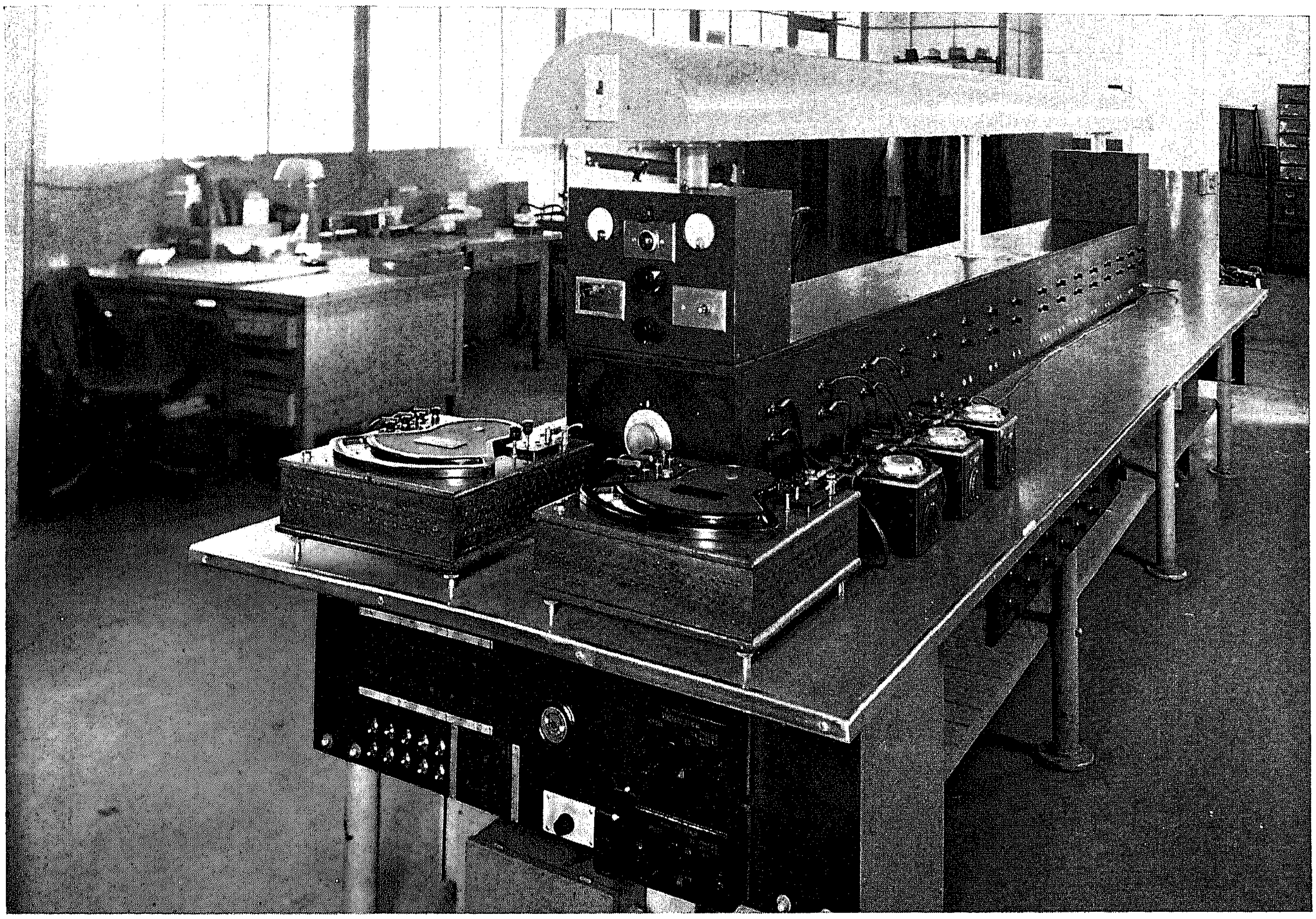


Fig. 7.—General view of the new automatic test board. The amplifier instruments and the time control are seen above the two indicating wattmeters, and the load-setting controls are seen below.

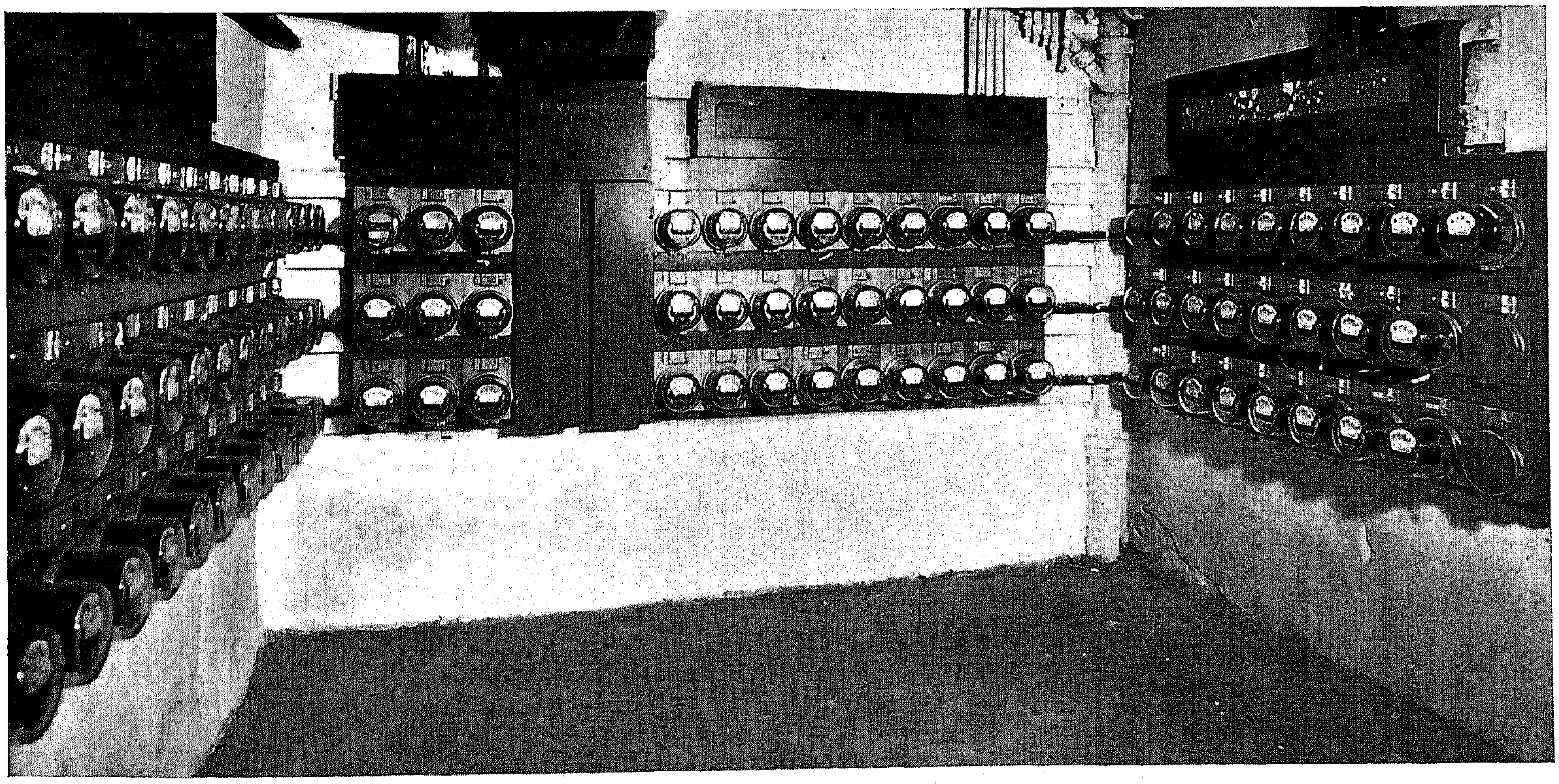


Fig. 16.—Battery of meters in New York.

Plate 4

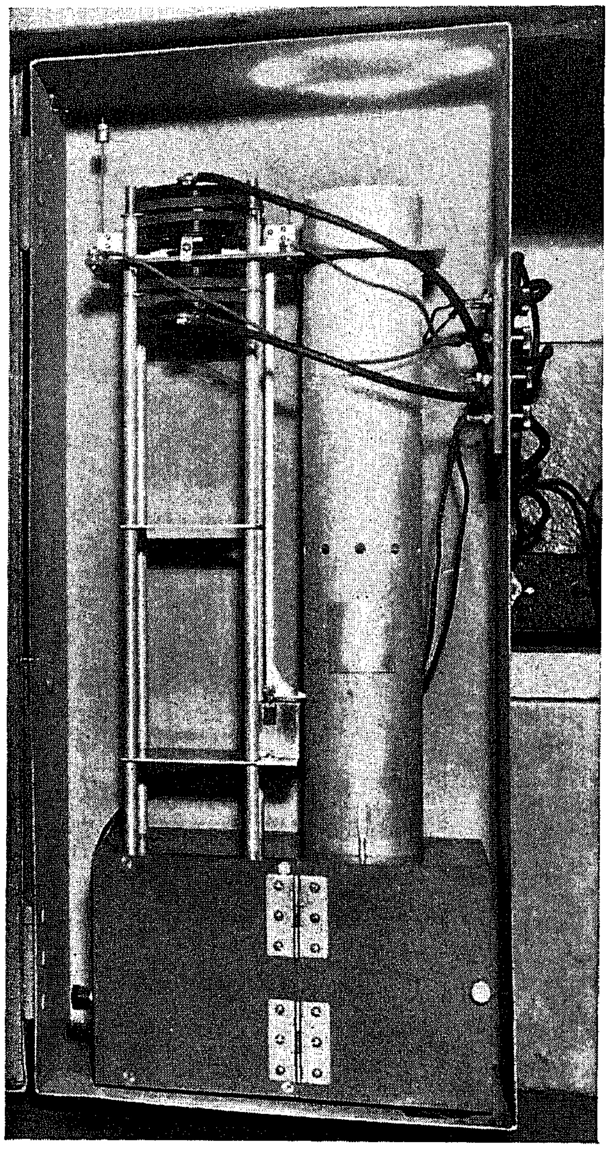


Fig. 8.—Control wattmeter and light-sensitive cell of the electronic current regulator, which is situated below the board surface.

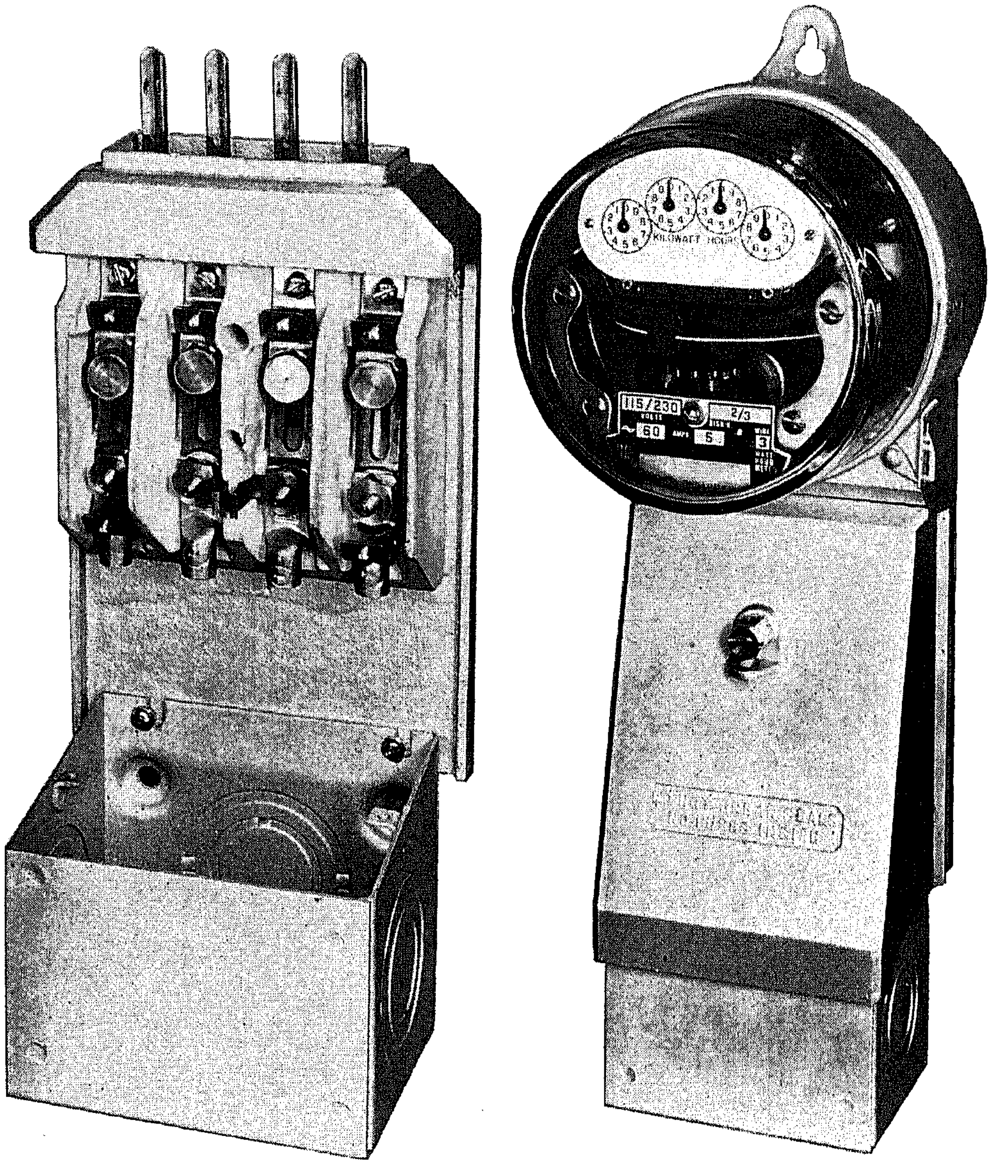


Fig. 12.—Type " A " meter installation.

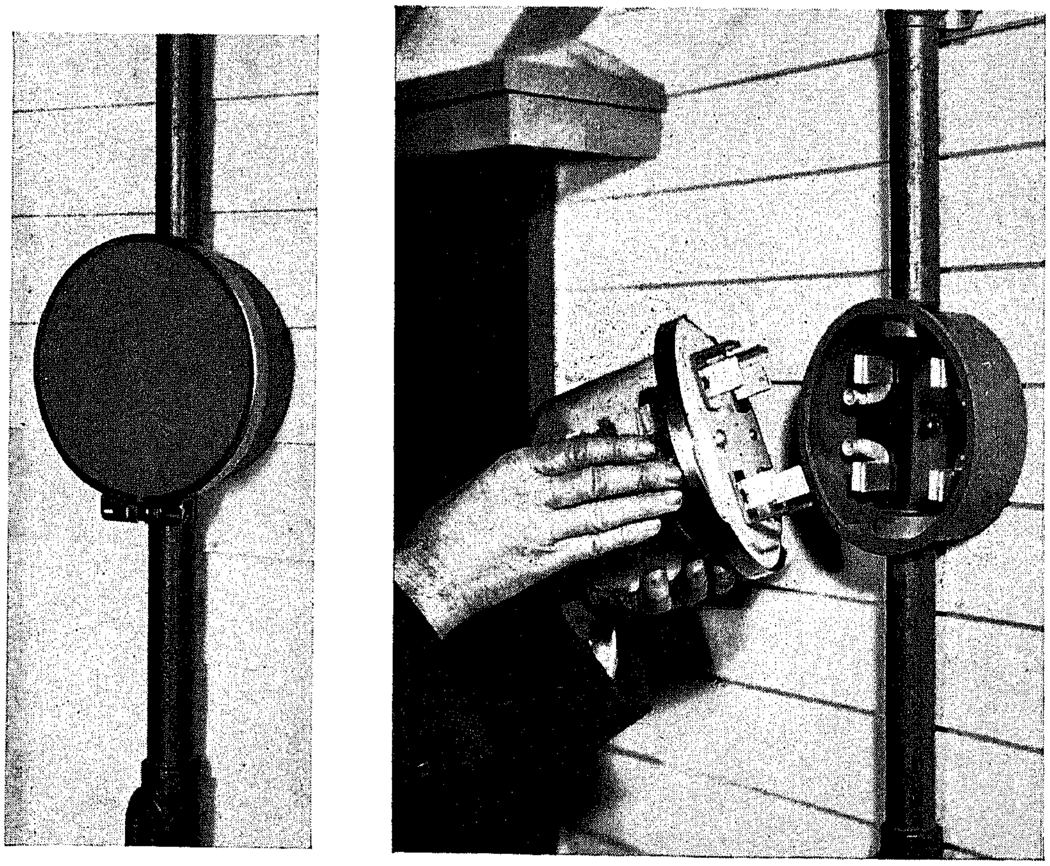


Fig. 13.—Type " S " meter installation.

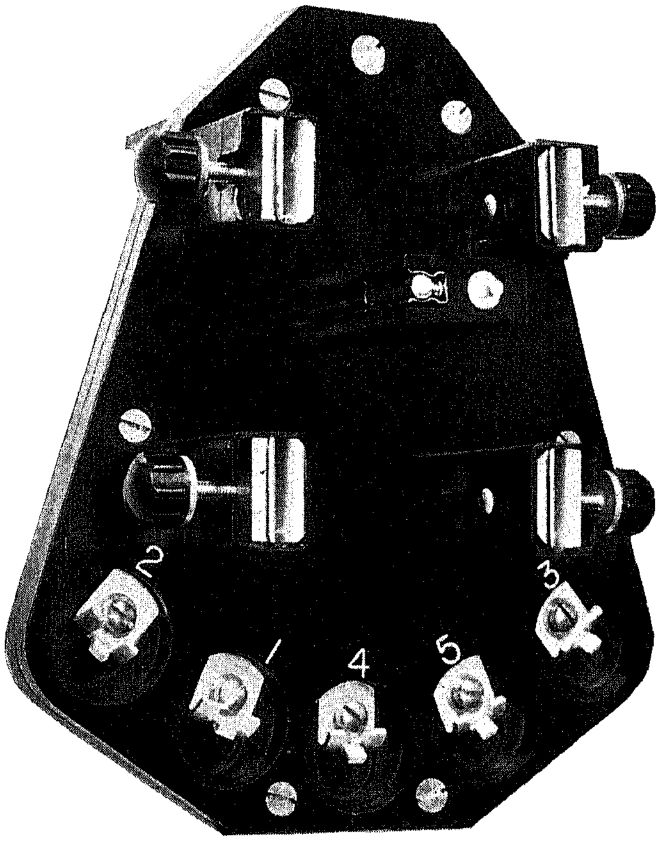


Fig. 14.—Test jack for type " S " meter.

meter is installed, as a result of a complaint made by the consumer.

" Section (9).—A periodic test is a test of a meter, made by an electric utility upon the premises where the meter is installed within the period specified in Sections (16) and (17).

" Section (10).—An office test is a test of a meter made by an electric utility upon the premises where the meter is installed, by the direction of an officer or employee of the utility that a test be made.

" Section (11).—A service test is a test of a meter, made by an electric utility, upon the premises where the meter is installed, during the period of temporary approval, by the Commission.

" Section (12).—A referee test is a test of a meter, upon the premises where the meter is installed, made or witnessed by representatives of the Public Service Commission."

Sections (16) and (17), mentioned in Section (9) above, form part of a very comprehensive schedule of testing for both a.c. and d.c. meters of various capacities, the length of time during which they are allowed to remain in service without retest varying inversely with their capacities. Examples of some of the time periods for single-phase and polyphase induction meters as given in these and the Regulations of the other Commissions are given in Table 2.

It should be noted that the voltage generally used in the United States for house-service supply is nominally 110, and in comparing the current ratings of meters this has to be borne in mind. The current ratings of the meters used in New York are 5, 15, and 50 amperes at 110 volts, compared with our present British Standard sizes of 2½, 5, 10, 25, and 50 amperes at 230 V. On the other hand, the difference in voltage would seem to necessitate the greater use of the 3-wire meter for greater capacities.

As a matter of interest, one of the types of supply transformers used is delta-connected, one leg being larger than the other two, tapped at the mid-point, and earthed. This means that the lighting is on a 3-wire single-phase supply with a nominal voltage of 110–120 V.

Table 2

Undertaking	Meter rating	Test period	Remarks
Single-phase induction meters			
New York	Up to 6 kVA From 6 to 60 kVA Above 60 kVA	6 years 2 years 1 year	
New Jersey	Up to 5·5 kVA Above 5·5 kVA	4 years 2 years	
Illinois	Up to 2·75 kVA Up to 2·75 kVA Above 2·75 kVA	5 years 2·5 years 2 years	N.E.L.A. Code type of meter Other types
Michigan	Up to 2·75 kVA Above 2·75 kVA	6 years 2 years	
Polyphase meters—metering equipments			
New York	Above 60 kVA	1 year	
New Jersey	Above 60 kVA	1 year	
Illinois	Above 50 kVA	1½ years	
Michigan	Up to 100 kVA Above 100 kVA	2 years 1 year	

Section 15 of this testing schedule is important and states that " each alternating-current watthour meter shall be tested prior to installation *or* within 60 days after installation." D.C. watt-hour meters have to be tested within 60 days after installation. The period of 60 days is the period of temporary approval quoted in Section (11), and this can be compared with the temporary approval granted by our Electricity Commissioners for " existing " apparatus.

Rules for testing.

Sections (19)–(23) deal with the testing of meters in service, specifying that this must be done under local operating conditions. They also cover the certificates which have to be provided for metering transformers and d.c. shunts, stipulating that a short-circuiting device must be fitted to a current transformer which cannot be removed from circuit.

An interesting addition to these rules for testing, which was made in 1937, relates to the testing on light load of meters having two registers. Here, the difference between the registration of each dial tested separately on light load must not exceed $\frac{1}{2}$ of 1 %. It should be emphasized that light load in America is 1/10th of full load and not 1/20th as in this country. Also full load usually refers to a point between 60 % and 100 % load. This is calculated on a " per element " basis.

Determination of accuracy.

Sections (24) and (25) relate to the determination of accuracy and stipulate that at least two tests, which must agree within 1 %, have to be made at each load. The author has already dealt with the method of calculating the final average accuracy. As previously stated, the meter must be adjusted to register accurately, or between correct and 2 % slow [Section (26)].

Determination of " creep."

The interesting point in Section (27) is that a meter is *not* considered to " creep " when on no load, with all house wires removed and with no current flowing in the consumer's circuit, unless the disc makes one revolution in 5 minutes or less. This means that the " creep " must be definite and not due to transient conditions.

Reporting tests.

Two sets of official forms are specified and illustrated, one for " periodic, complaint, and office tests " and another for " service tests," the reports of each test having to be filed with the Commission each month.

This concludes a general survey of the New York Commission's regulations so far as they can be compared with our own, and the author feels that the extracts given are fairly representative of the views of the other Commissions in regard to watt-hour metering practice. Again he would like to state, however, that they are all more comprehensive than our own (as so far issued), the New York Commission's Regulations going on to cover block interval type indicating and graphic demand meters, printing type demand meters, and contactor devices along similar lines.

ACTUAL TESTS

Standards and Substandards

The author has already mentioned that the types of standard and substandard instruments used in America are practically identical with our own, and it follows that their methods used for standardizing and checking are also very similar to ours. There are one or two differences, of course, an important point being that the Americans have, to a large extent, eliminated the use of stop-watches, the timing being effected by impulses from the standard clock. This is achieved with the aid of a photo-electric cell. Briefly, the method consists of holding a constant load on the rotating substandards under test for a definite time period with the potential circuit of these instruments controlled from the standard clock. An ingenious extension of automatic control methods of testing rotating substandards is that developed by the Consolidated Edison Co., New York. In addition to automatic time control, an automatic load controller is used which holds the load steady within 0·05 %, with the supply off the mains. A general view of this equipment is shown in Fig. 7 (see Plate 3), where the amplifier instruments and time control are seen above the two indicating wattmeters, and the load-setting controls are seen on the board below them. Fig. 8 (see Plate 4) gives an illustration of the cabinet containing the control wattmeter and light-sensitive cell.

Fig. 9 gives a circuit diagram of this equipment, which the author saw demonstrated; he was extremely impressed by its performance. He thinks that it has great possibilities and is well worth considering for use in this country.

An automatic load control for testing rotating substandards is also used by the Public Service Electric and Gas Co. of New Jersey. In this case a graphic recorder is added, the chart being marked by the standard clock impulses.

Methods of Testing Service Meters in the Laboratory

The methods, although varying among themselves, are generally on the same lines as those used in this country, i.e. the comparison method, using a rotating standard, and testing meters either singly or in batches. A method which appears to be becoming popular is the use of a rotating standard fitted with a stroboscopic attachment, one meter at a time being tested. This method is used exclusively by the Westinghouse Co. in their meter factory. It is doubtful whether any advantage would be obtained by its use in this country, as the lowest load at which it is effective is 1/10th, and it was admitted by the above Company that it would not be satisfactory at our lowest load of 1/20th. The reason for this is, of course, that the velocity of an induction meter disc at this low speed is not uniform, and even at 1/10th load a considerable amount of oscillation can be shown up by the method. It would be impossible in the case of some of the older pattern meters to attempt even 1/10th load. With the types of meters which the Westinghouse Co. are producing, however, the method appeared to be very satisfactory.

It is interesting to note that the dial method of testing (Method A in our Regulations) is not used in America, the dials being checked by either mechanical or electrical means.

Current and Potential Transformer Testing

The methods adopted in the States for testing current and potential transformers are generally very similar to our own, the use of the Silsbee apparatus appearing to be the most popular.

Site Testing

The author has previously stated that it is a universal practice in America to test meters on site by means of portable rotating induction-type substandards and " artificial " loads. As far as he is aware this method is generally applied in this country only to large transformer-operated equipments. He has already dealt with the suitability of using an accurate check meter where the load permits sufficiently accurate readings to be taken. One point which does not appear to be quite clear, however, is that certain Regulations refer to tests on site which have to be taken " under local operating conditions." This might be interpreted to mean that a dial test instrument should be used.

Incidentally, testing on site also applies to maximum-demand instruments, block interval type indicating and graphic demand meters, printing type demand meters, etc.

Servicing in Laboratory

The author has already dealt with the general practice of servicing meters on site, but he would like to make some observations on American laboratory servicing methods. Generally speaking, he found their methods very similar to those adopted by his own Company. It was interesting to interchange ideas on common difficulties, and a mention of one of the novelties which he saw may be of value. This was a chemical method for cleaning badly corroded and tarnished clockworks and other types of mechanisms. The method is employed by several companies and consists of the use of a rotating cleaner containing one or more solutions in which the clockwork is immersed for a short time. Similar apparatus for cleaning watches and clocks has been on the market in America for some years and the method would appear to have considerable possibilities.

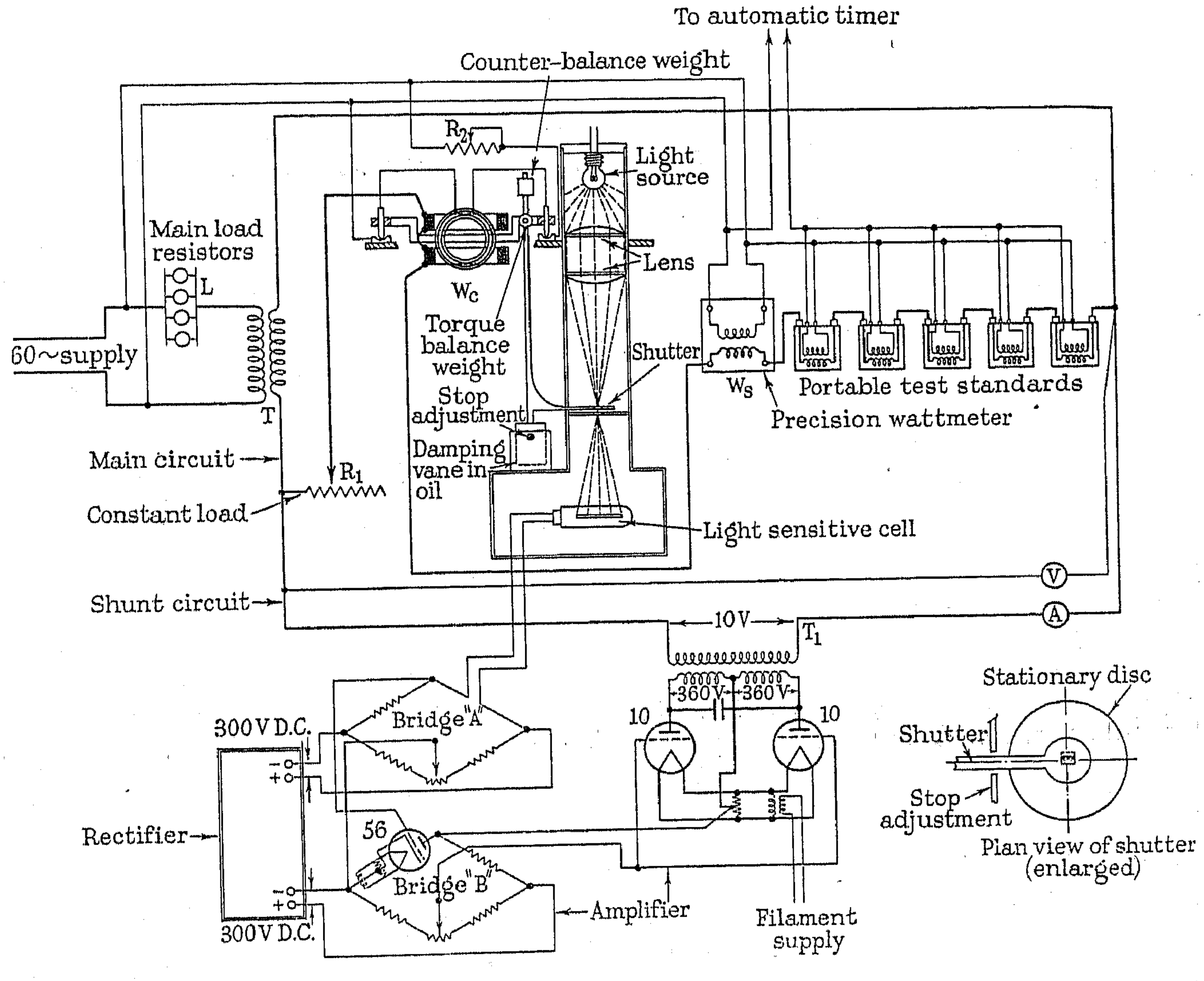


Fig. 9.—Electronic current regulator. Circuit for holding constant watt load on portable standards while under test.

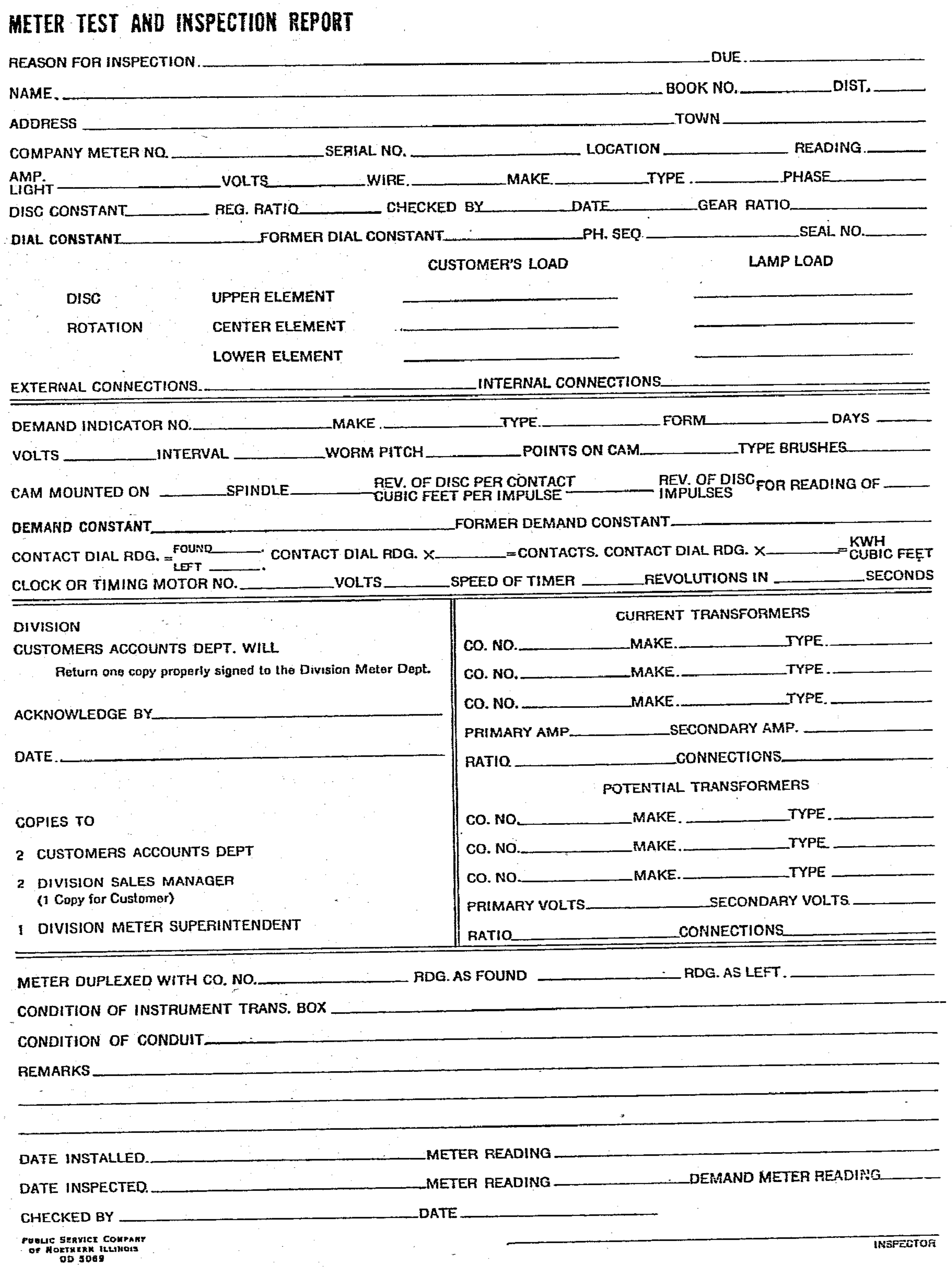
All the engineers whom the author visited were extremely interested in the steam cleaning method and technique for cleaning jewels developed by his Company. Details of this equipment were supplied to them and it is understood that they are considering its use.

Microscopic examination of pivots and jewels is employed in all the servicing laboratories which the author saw.

RECORDS

The author was impressed by the nature of the records kept by all the companies which he visited. Periodic testing and overhauling on site obviously necessitates a very comprehensive and highly organized system of records, particularly when large numbers of meters are in service. The forms which have to be filled in require detailed information regarding not only the " as found " and " as left " accuracy of the meter but also full details of its mechanical and electrical condition. As an example, Figs. 10 and 11 show two of the forms used by the Public Service Co. of Northern Illinois.

Some of the equipment used for keeping records is extremely elaborate. For instance, the Consolidated Edison Co., New York, has a machine which automatically produces, at the touch of a button, a complete analysis of any particular work which has been carried out on the meters. Briefly, this machine automatically selects cards punched according to the particular work



METER TEST AND INSPECTION REPORT

REASON FOR INSPECTION ______ DUE ______
NAME ______ BOOK NO. ______ DIST. ______
ADDRESS ______ TOWN ______
COMPANY METER NO. ______ SERIAL NO. ______ LOCATION ______ READING ______
AMP. LIGHT ______ VOLTS ______ WIRE ______ MAKE ______ TYPE ______ PHASE ______
DISC CONSTANT ______ REG. RATIO ______ CHECKED BY ______ DATE ______ GEAR RATIO ______
DIAL CONSTANT ______ FORMER DIAL CONSTANT ______ PH. SEQ ______ SEAL NO. ______

		CUSTOMER'S LOAD	LAMP LOAD
DISC	UPPER ELEMENT		
ROTATION	CENTER ELEMENT		
	LOWER ELEMENT		

EXTERNAL CONNECTIONS ______ INTERNAL CONNECTIONS ______

DEMAND INDICATOR NO. ______ MAKE ______ TYPE ______ FORM ______ DAYS ______
VOLTS ______ INTERVAL ______ WORM PITCH ______ POINTS ON CAM ______ TYPE BRUSHES ______
CAM MOUNTED ON ______ SPINDLE ______ REV. OF DISC PER CONTACT / CUBIC FEET PER IMPULSE ______ REV. OF DISC / IMPULSES FOR READING OF ______
DEMAND CONSTANT ______ FORMER DEMAND CONSTANT ______
CONTACT DIAL RDG. = FOUND ______ LEFT ______ CONTACT DIAL RDG. × ______ = CONTACTS. CONTACT DIAL RDG. × ______ = KWH / CUBIC FEET
CLOCK OR TIMING MOTOR NO. ______ VOLTS ______ SPEED OF TIMER ______ REVOLUTIONS IN ______ SECONDS

DIVISION
CUSTOMERS ACCOUNTS DEPT. WILL
Return one copy properly signed to the Division Meter Dept.
ACKNOWLEDGE BY ______
DATE ______

COPIES TO
2 CUSTOMERS ACCOUNTS DEPT
2 DIVISION SALES MANAGER (1 Copy for Customer)
1 DIVISION METER SUPERINTENDENT

CURRENT TRANSFORMERS
CO. NO. ______ MAKE ______ TYPE ______
CO. NO. ______ MAKE ______ TYPE ______
CO. NO. ______ MAKE ______ TYPE ______
PRIMARY AMP ______ SECONDARY AMP. ______
RATIO ______ CONNECTIONS ______

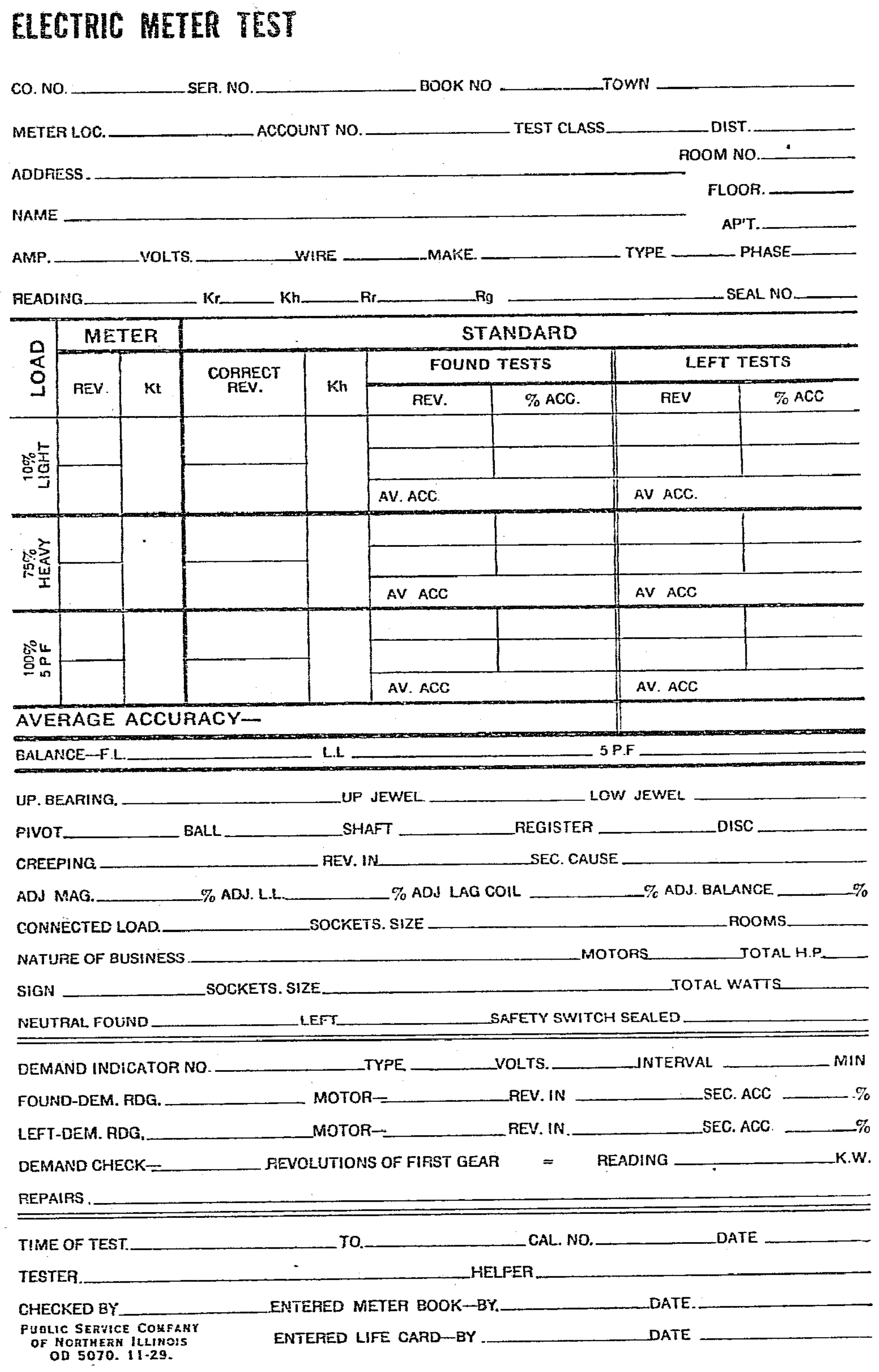
POTENTIAL TRANSFORMERS
CO. NO. ______ MAKE ______ TYPE ______
CO. NO. ______ MAKE ______ TYPE ______
CO. NO. ______ MAKE ______ TYPE ______
PRIMARY VOLTS ______ SECONDARY VOLTS ______
RATIO ______ CONNECTIONS ______

METER DUPLEXED WITH CO. NO. ______ RDG. AS FOUND ______ RDG. AS LEFT ______
CONDITION OF INSTRUMENT TRANS. BOX ______
CONDITION OF CONDUIT ______
REMARKS ______

DATE INSTALLED ______ METER READING ______
DATE INSPECTED ______ METER READING ______ DEMAND METER READING ______
CHECKED BY ______ DATE ______
______ INSPECTOR

PUBLIC SERVICE COMPANY OF NORTHERN ILLINOIS OD 5069

Fig. 10



ELECTRIC METER TEST

CO. NO. ______ SER. NO. ______ BOOK NO ______ TOWN ______
METER LOC. ______ ACCOUNT NO. ______ TEST CLASS ______ DIST. ______
ADDRESS ______ ROOM NO. ______
FLOOR ______
NAME ______ AP'T. ______
AMP. ______ VOLTS ______ WIRE ______ MAKE ______ TYPE ______ PHASE ______
READING ______ Kr ______ Kh ______ Rr ______ Rg ______ SEAL NO. ______

LOAD	METER		STANDARD		FOUND TESTS		LEFT TESTS	
	REV.	Kt	CORRECT REV.	Kh	REV.	% ACC.	REV	% ACC
10% LIGHT								
					AV. ACC		AV. ACC.	
75% HEAVY								
					AV ACC		AV ACC	
100% 5 P F								
					AV. ACC		AV. ACC	

AVERAGE ACCURACY—
BALANCE—F.L. ______ L.L ______ 5 P.F ______

UP. BEARING ______ UP JEWEL ______ LOW JEWEL ______
PIVOT ______ BALL ______ SHAFT ______ REGISTER ______ DISC ______
CREEPING ______ REV. IN ______ SEC. CAUSE ______
ADJ MAG. ______ % ADJ. L.L. ______ % ADJ LAG COIL ______ % ADJ. BALANCE ______ %
CONNECTED LOAD ______ SOCKETS. SIZE ______ ROOMS ______
NATURE OF BUSINESS ______ MOTORS ______ TOTAL H.P. ______
SIGN ______ SOCKETS. SIZE ______ TOTAL WATTS ______
NEUTRAL FOUND ______ LEFT ______ SAFETY SWITCH SEALED ______

DEMAND INDICATOR NO. ______ TYPE ______ VOLTS ______ INTERVAL ______ MIN
FOUND-DEM. RDG. ______ MOTOR— ______ REV. IN ______ SEC. ACC ______ %
LEFT-DEM. RDG. ______ MOTOR— ______ REV. IN ______ SEC. ACC ______ %
DEMAND CHECK— ______ REVOLUTIONS OF FIRST GEAR = READING ______ K.W.
REPAIRS ______

TIME OF TEST ______ TO ______ CAL. NO. ______ DATE ______
TESTER ______ HELPER ______
CHECKED BY ______ ENTERED METER BOOK—BY ______ DATE ______
ENTERED LIFE CARD—BY ______ DATE ______

PUBLIC SERVICE COMPANY OF NORTHERN ILLINOIS OD 5070. 11-29.

Fig. 11

Meter test sheets used by the Public Service Company of Northern Illinois.

which they record. To push a button and obtain a complete analysis on, say, replacements of bearings, seems to the author to be approaching the meter engineer's millennium.

The author has no doubt that the systems in use have been found necessary and that they do make for efficiency, but he is a little doubtful whether they could be economically applied in this country at the present time.

COSTS

The author collected a fair amount of information regarding costs. It will be appreciated, however, that it is extremely difficult to compare the figures of the American companies with costs in this country because, apart from the cost-of-living factor, once again their methods of testing are entirely different from ours.

As examples of labour costs, however, some approximate figures may be given. The Consolidated Edison Co. pay an outside tester £5 15s. 4d. per week, and an engineer capable of testing large equipments £9 per week. The cost of " site " testing a single-phase meter in this company is approximately 3s.

The Detroit Edison Co. pay 30s. per day for 14 meters per man, the cost being approximately 2s. 1¾d. per meter. The Commonwealth Edison Co. give their cost as 2s. 8½d. per meter, while the Public Service Co., Illinois, quote a cost of just over 4s. per meter, this higher cost being probably accounted for by the fact that the Company operates over a fairly large rural area.

In considering these costs, however, several points have to be borne in mind. First of all the Americans, by carrying out periodic tests and overhauling on site, eliminate removal, transport, and re-installation costs. On the other hand, they test every meter for " as found " accuracy. The difference between these costs, if any, must be taken into consideration.

Again, the American companies have to retest their meters at more frequent intervals than those usually appertaining in this country, and thus their total costs are correspondingly higher.

While on the subject of the cost of testing for " as found " accuracy, the author would like to mention the following as being the most economic method, particularly where large numbers of meters are concerned:—

(1) A periodic analysis carried out on selected meters returned from service. (This determines the permanent-magnet ageing and the valuation of the increase in friction at the points where this can occur.)

(2) A sampling of service meters over shorter periods than 7 years (Northmet period).

(3) The analysis of meters returned for other reasons, such as special tests.

(4) Preliminary tests on meters after overhaul and before adjustment. (This test can be carried out on all meters returned from service and is an extremely valuable check on the stability of permanent magnets and electromagnetic structure.)

This method enables sufficient data to be obtained regarding the condition of the meters returned from service without incurring the expense of testing every meter before overhaul.

DEVELOPMENTS

Standardized Meters

Widely varying climatic conditions have influenced metering developments in America in many ways. All makes of American meters have been fully temperature-compensated for many years, and with the use of the outdoor plug-in type of installation it will be appreciated that this form of compensation is absolutely essential.

Standardization on meter bases has been carried out by all manufacturers so that they all use the same mounting dimensions to cover two classes of meters. These are known as the " A " and " S " types and in both cases the meters can be detached without disturbing the connections. The " A " type is designed for bottom connections, and a good idea of the plug-in terminal facilities can be obtained from Fig. 12. The " S " or socket type meter is illustrated in Fig. 13, which shows a typical outdoor installation. Fig. 14 (see Plate 4) shows a test jack for " S " type meters; this device eliminates the necessity for permanent test facilities for each meter.

The application of the " S " type of mounting to polyphase meters is illustrated in Fig. 15. A typical view of a battery of meters in an installation in New York is shown in Fig. 16 (see Plate 3).

An important point regarding this standardization of meter bases is that old types of meters can be converted into either the " A " or " S " type of mounting. From the examples shown it will also be noted that it is practically impossible for any form of pilfering to take place.

Bearings

Outdoor metering has entailed difficulties in regard to the use of oil in both top and bottom bearings. The attention of American engineers has consequently been concentrated on the use of not only a dry bottom bearing but also a dry top bearing. The author was informed that good results had been obtained in Chicago with a dry top bearing made of bronze. It is obvious that such a bearing would have to be made with great precision to reduce " chatter " to a minimum, although this disadvantage would be of no consequence in outdoor installations.

The dry bottom bearing is of the ball kind, this being the principal type which it is considered to be possible to run dry successfully. The bearing consists of a ball between two cupped sapphires, the ball being either of carbon steel or of stainless steel. The latter material is the more popular and the author believes that experiments are also being made with other metals. The design has been fostered largely by the Westinghouse Co., and the utilities using the bearing claim that it gives a longer life than the pivoted type, although they admit that it has a tendency to be noisy and requires levelling.

The result of observations of the American statistics leads the author to think that although the ball type appears to be superior to the pivot type, further research is necessary before any definite conclusions can be formulated. He is not yet convinced that the ball type is necessarily any better than the pivot type where oil

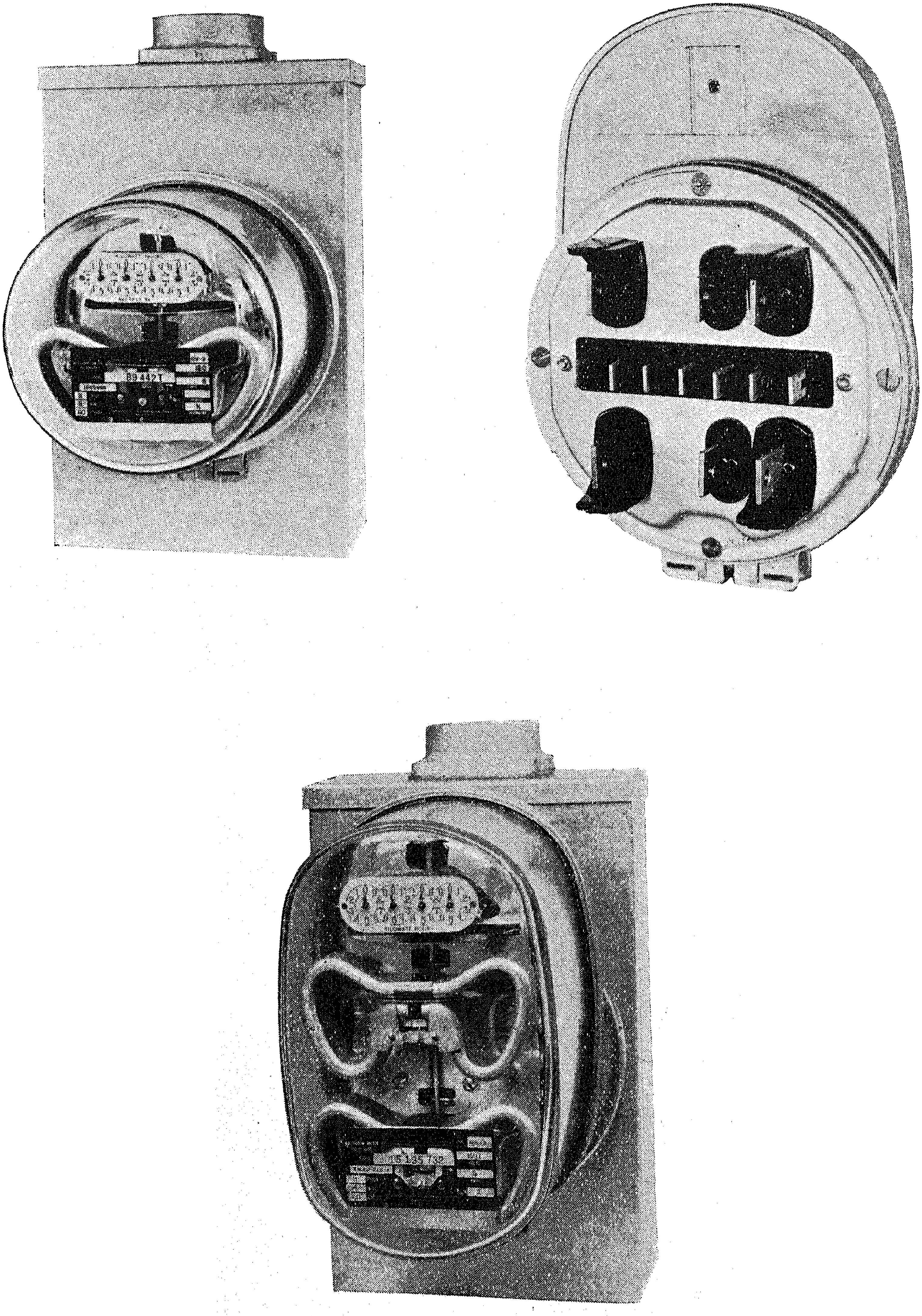


Fig. 15.—Polyphase type " S " installations.

can be used, provided that the oil is of the correct grade and that selected jewels having the correct optic axis are used.

It appeared to the author that American engineers have paid more attention to the development of pivot design and material than to the sapphire jewel. An illustration of this trend is evidenced in the Duncan Nobeloy pivot, which contains gold and platinum. The tip of this pivot is slightly rounded so that it conforms closely to the curvature of the jewel cup. This has the effect of reducing the high pressure exerted on the jewel, although the area of contact is increased. In recent years research in this country has perhaps been more concentrated on the jewel, although a considerable amount of work has been, and is still being, carried out on pivots. In this connection it is interesting to record that the Public Service Co., New Jersey, is now using selected oriented cut jewels.

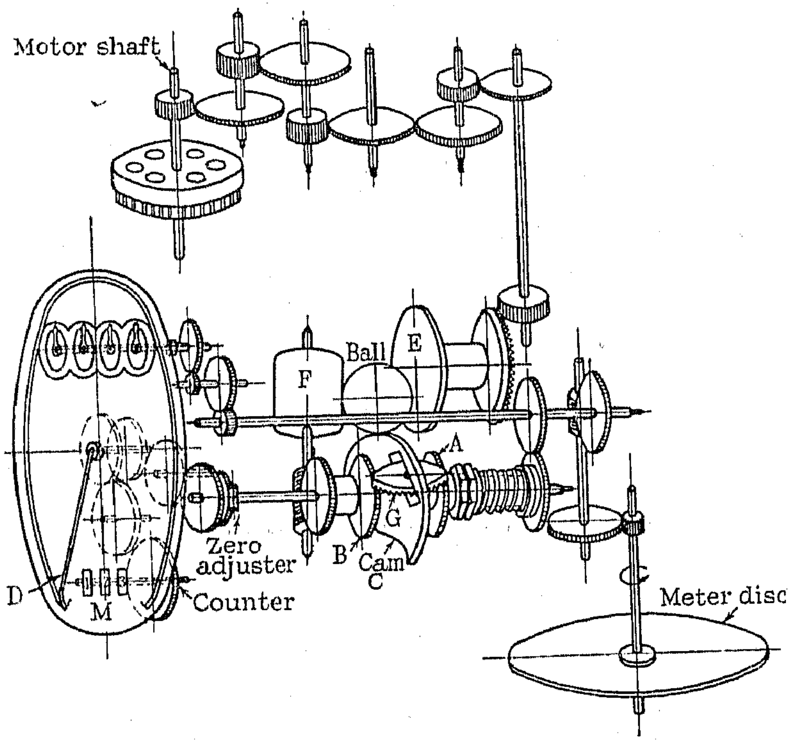


Fig. 17.—Diagrammatic arrangement showing principle of operation of logarithmic demand attachment.

A.—Watt-hour meter side of differential.
B.—Timing side of differential.
C.—Involute cam carried by centre of differentials.
D.—Demand hand.
E.—Disc driving ball.
F.—Drum driven from ball.
G.—Planetary gear of differential.
M.—Totalized demand record.

Demand Metering

The kilowatt-hour maximum-demand instruments of the Merz type are extensively used in the States. A recent development in connection with this mechanism is known as the "cumulative demand attachment," which totalizes the demand on a set of dials in place of the usual single pointer, each period demand being added to the preceding demand. The result is that the demand reading is never lost due to periodical resetting. The other types of instrument are also used, one type being the Lincoln thermal-demand instrument which is arranged for either kilowatt or ampere demand. Demand metering practice in America differs slightly from ours, inasmuch as in certain cases they favour the thermal law as applied to demand measurement, rather than the Merz system. As a matter of fact the Westinghouse Co. manufacture a mechanical demand register which can be fitted to a standard kilowatt-hour meter. This follows the same logarithmic law as a purely thermal instrument and gives similar time periods. A diagrammatic sketch showing the principle of this mechanism is given in Fig. 17.

Polyphase Metering

The single-disc polyphase meter for 3-phase 3-wire and 4-wire supplies has been developed by American manufacturers. Briefly, the disc consists of a number of laminations which are cemented together by a special process. The laminations are insulated from one another and are slotted to prevent eddy-current interaction.

General

Other general developments concern the use of two-rate double-dial meters and meters which incorporate a time switch. As far as the author is aware, practically no prepayment meters are being used and, in this respect, he thinks that American engineers are possibly to be envied. He was given to understand that in most cases where prepayment meters were tried, they had to be swiftly removed in favour of a straightforward meter.

CONCLUSION AND ACKNOWLEDGMENTS

It will be appreciated that it is extremely difficult to deal adequately with all the aspects which come within the scope of a survey of this nature. The author has endeavoured, however, to mention those which he considers to be of particular interest to meter engineers at the present time.

In conclusion, he would like to place on record his sincere appreciation of the unfailing courtesy with which he was received by all the engineers whom he met in America. They did everything in their power to place at his disposal any information which he required and were equally ready to interchange ideas, not only during his stay but in the future. From this point of view alone the author thinks that his visit was of very real value. He wishes to make acknowledgments to Mr. Allen of the Consolidated Edison Co., New York, and to Mr. Albright of the Detroit Edison Co., Detroit, for their kind permission to reproduce the illustrations concerning their utilities.

He is also grateful to the late Mr. R. C. Lanphier, sen., and other members of the Sangamo Electric Co. for their personal interest and assistance throughout the tour.

Finally, the author would like to express his very grateful thanks to the Directors of the North Metropolitan Electric Power Supply Co. for giving him the opportunity of making the tour and for allowing him to publish his experiences in this paper.

[The discussion on this paper will be found on page 208.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 14TH APRIL, 1939

Mr. E. W. Hill: When I took up this paper for the first time I was afraid that I was going to read that this country was being outclassed by the U.S.A. in every branch of metering activity. I was therefore reassured by the author's statement to the effect that our best is as good as theirs. The next sentence in the paper states, however, that our general level is not nearly so good as their general level, and this is not to be wondered at seeing that we have had to contend with a 40-year-old Act of Parliament, with no penalties for breaches of its clauses, which was virtually treated as a dead letter. Again, the attitude of responsible supply authorities, with a few exceptions, has exhibited to say the least a certain lack of sympathy. However, we should hope that within the next few years our general level will noticeably rise after a further experience of our own Meters Act.

It cannot call for anything but our admiring and envying comment when we see, by way of contrast, the splendid departments shown in the photographic illustrations in the paper. Admittedly the expense involved must have been high, but one cannot suppose that American public utilities would sanction such outlay unless they confidently expected some return.

One can hardly refrain from comment on the fact of there being only four meter firms in the U.S.A. We know that in the U.S.A. they have no difficulty in completely excluding foreign competition; but how do they manage to discourage so effectually internal competition?

The author records, without approval I gather (and I agree with him), the widespread practice in America of servicing on site. I submit that the British practice of test-house servicing is superior, and it is significant that two American companies are considering the abandonment, after long usage, of their method in favour of ours.

The prevalence of fraudulent diversion of current from the meter has driven the U.S.A. engineers to adopt iron-clad installations and, in particular, outdoor installation. The latter certainly allows for easy access and also tends to prevent fraudulent tricks on meters by reason of their being open to more or less continuous public observation. I cannot, however, see what particular advantage there is in the American use of plug-in type meters as compared with our much simpler method of efficiently designed extended terminal covers. I think the American practice must cost more both for meter and for installation details, without providing any better safeguard; for if, as the author says, the consumers pay little regard to seals then seals can be broken (and responsibility repudiated as the meters are open to be tampered with by any passer-by), and the meter could even be removed and a diversion device surreptitiously inserted and the meter put back, and nobody would be any the wiser, as all the plug-in connections are so effectively concealed.

As regards the American accuracy regulations, one is struck with the adoption of the two sets of limits used, namely the "as left" and the "as found." This clearly gives official recognition of the fact that after a period of service a meter's accuracy may depreciate, and so the "as found" limits are considerably wider than the "as left." It would, however, be a dangerous fallacy, I think, to liken these regulations to our own legal limits. Actually, it will be found upon consideration that here we have nothing that corresponds at all closely to these American regulations. That is due to the fact that our Act of 1899 still holds the field as regards accuracy limits and has never been revised to bring it into line with modern conditions and requirements. Our position is, by virtue of the said Act, that so long as the error of a meter does not exceed $+ 2\frac{1}{2}$ % or $- 3\frac{1}{2}$ % it is a legally correct meter whose registration cannot be challenged by the consumer. In fact, as the Commissioners' limits of $+ 2\frac{1}{2}$ % and $- 3\frac{1}{2}$ % are prescribed by them for any load at which the meter may be operating, we may infer that no particular loads such as full load or 1/20th load are specified by the Commissioners because of the risk that if a disputed meter were found to be operating outside—either above or below—any such specified range of load it might be successfully maintained in a court of law that because no limits of error were specified for such loading therefore the meter was not a legal instrument and the account could on those grounds be repudiated.

It is to be noted that the intention of the American limits is not that meters may be deliberately set in error by the amount of the tolerance. This might well be copied by us.

In comparing their limits with our legal limits I should at least like to draw one comparison in our favour, and that is that according to the examples cited in the paper their limits are in several instances much laxer than ours. For instance, they have in two undertakings "as left" limits of ± 3 % at light load, and we must remember that this (see page 202) is 1/10th load and not 1/20th. Furthermore, in three undertakings they have a calculated average error of ± 4 %, which is greater than our $+ 2\frac{1}{2}$ % and $- 3\frac{1}{2}$ % legal limits at all operating loads. Again, they have no prepayment meters to make things harder as regards accuracy limits.

I do not approve the American method of calculating the "as found" average error—to weight the full-load error by multiplying it by 4 seems too much like a rule-of-thumb method. If it is impossible in case of a dispute to assess the loading under which a meter has been operating with a reasonable estimate, then a good straight-line-characteristic check meter installed on site should be the answer to the difficulty. If this cannot be used because the load is so low that too long a run is necessitated, then at least the loading is known and the other method can be used.

Table 2, giving the time-intervals allowable between periodic tests, is very interesting. I am reminded that the Meter Engineers' Technical Association drew up, in its published *Proceedings* for March, 1928, some recommendations which were: for a.c. single-phase, 5 years; for polyphase, 3 years up to 50 kVA, and 1 year above 50 kVA. It is surprising and gratifying to see how even at that date we over here appreciated what were reasonable values for the intervals, as they correspond quite closely to the modern American usage. One thing stands out, however, namely that it is so rare for us to have single-phase supplies exceeding 10 kVA that we did not, in these M.E.T.A. recommendations, think it necessary to legislate for sizes above 10 kVA; but apparently single-phase meters up to and even over 60 kVA are used in the U.S.A.

With regard to the determination of creep (page 202), it is wrong to condone a meter whose rotor may revolve, say, once every 5½ minutes. It is not at all unusual to have a meter of such a capacity that its gearing constant is 1 revolution or less per kWh. Such a meter then would not be regarded in the U.S.A. as creeping even if its disc were revolving once every 6 minutes, although it would then be adding to the record something more than 10 units every hour or over 240 per day. I cannot imagine that being allowed over here.

The reason why dial testing method " A " is not used in the United States is that American meters are not provided with testing dials. At a recent meeting of this Section* we found that there was a very great deal to be said for the use of method " A " in appropriate circumstances, and possibly America has something to learn from us in this respect.

Turning to the question of bearings, my impression derived from the paper is that ball bearings are used not because they are inherently better than the pivot type but because they can be used without oil (whereas pivots, we believe, cannot), and with meters installed out of doors one cannot risk having a lubricant in the bearings.

According to the author, American supply undertakings have to fill up very comprehensive forms giving the results of their meter tests. Are these tests checked by any higher authority? In short, is there anything corresponding to our officially certified meters?

In conclusion, I should like the author to tell us what, in his opinion, is the reason why prepayment meters cannot be used in the United States.

Mr. S. H. Richards: In reading the paper one cannot help being struck by the fact that testing departments in the U.S.A. have not merely grown up, but that the experience of years has been consolidated in efficient and well-planned test-rooms constructed for the work in which they are engaged.

The legal standard of accuracy for meters in England gives a wider band than that associated with American practice, and in many respects allows of coarser adjustment. It has to be remembered that there are meters in this country which have been on circuit for over 30 years, meters which one would have considered had passed the end of their useful life. Without the wide tolerance band allowed, such meters would not be able to pass the test which is called for. Whether such meters should still be used must be a matter of opinion, but I am convinced that their inaccuracies at low loads must seriously affect the revenue return to the undertaking.

I have been permitted to state that the Electricity Commissioners have set up a meter technical committee, which is investigating certain factors that have arisen since the coming into operation of the Electricity Supply (Meters) Act, 1936, with respect to the care and use of standard and sub-standard apparatus; recommendations with regard to test-room and repair-room practice; and the effect of storage and transport on life accuracy and the testing of disputed meters. This work has been found necessary in view of the misconstruction placed on the documents that have been issued previously, and to amplify the recommendations that have been made.

The testing of disputed meters has not received in this country the attention it deserves. An investigation into methods of procedure shows that the peculiarity of the individual rather than the accuracy of the meter is of paramount importance. A consumer who challenges the accuracy of his meter is concerned not with its curve accuracy but rather with the average weighted error in relation to the conditions controlling the method by which he takes his supply. The simpler method of test is undoubtedly that of inserting a meter in series. The accuracy of the reference meter, however, should be of sub-standard grade. Where a meter is returned from circuit some arbitrary method of obtaining the weighted error is necessary, and that employed in the United States is as simple as any.

I am impressed by the close attention given to records in the U.S.A. Periodic overhauls and testing are not of much use unless a comprehensive record system is in use. The characteristics and conditions of service of meters and the life accuracy of any particular type can only be gauged by a close inspection of a statistical record of tests. Such a system need not be costly to be efficient, and can materially improve circuit accuracy, which is after all the thing that counts.

The paper would have been still more valuable if it had laid emphasis on the personnel employed in testing stations in the U.S.A. It is abundantly evident from the paper that they must have had the best theoretical and practical training. This fact has two aspects, namely: (1) The appreciation by those in charge of undertakings of the importance of highly trained technical staffs for testing stations. (2) The appreciation by the staff themselves of the importance of their work and the necessity for training to fit them for the work they have to do.

I feel that some account of American methods of transport from the testing station to the site should be included in the paper. Has any relation been noted between laboratory and site tests in the U.S.A.? If so, what has been been done to lessen the difference between the results shown by the two types of tests? Do American supply undertakings send out meters on the handlebars of cycles?

Mr. O. Howarth: It is unfortunate that our Electricity Supply (Meters) Act does not call for periodic return of meters; apparently certification has no time limit. I do not agree that accuracy cannot be achieved without additional regulations under that Act. If an examiner came along with his instruments and checked a sample of the meters which had been tested we should probably achieve as much accuracy as by issuing a lot of regulations.

American engineers are apparently not restricted in regard to their expenditure; I doubt if this is a good thing. It is better that we should have to justify the expenditure of money. Extravagance in capital expenditure is a much more serious matter than extravagance in revenue expenditure, because it continues for all time and puts up the costs of testing permanently.

Has the practice of testing on site which is prevalent in America grown up from the early days without being carefully planned? So far as we in this country are concerned, tests of meters removed from service show that our methods are sound. From time to time, at the request of disgruntled consumers, most undertakings fix check meters on site, and the results obtained indicate that the meters in service are registering accurately.

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* See *Journal I.E.E.*, 1938, **82**, p. 421.

Apart, perhaps, from the figures for New York, the permissible errors shown in Table 1 seem to be no smaller than the errors permitted in this country, but it depends upon what is meant by the calculated average error. A calculated average error of ± 4 % permits of very much greater errors than our present limits of $+ 2\frac{1}{2}$ % and $- 3\frac{1}{2}$ %. The value of specifying "as left" errors is not really very great. The errors specified by the Commissioners may not be exceeded at any load at which the meter may be working, at any temperature, and at any time. These requirements compel us to work within an error of $1\frac{1}{2}$ % in the testing station, and I imagine that this corresponds to 1 % on site because of the additional errors which may creep in with on-site testing.

There is one way in which I think the Americans have scored over us, and that is with regard to the standardizing laboratory mentioned on page 200. According to the paper no laboratory is deemed properly equipped as a standardizing laboratory until it has been inspected and has received a certificate of approval from the Commission. In this country we only have to have our instruments approved.

I do not agree with the author's view, expressed on page 200, that 6 months is too long a period between tests of instruments. A good instrument might reasonably be expected to last 6 months without appreciably changing its error. However much the period is reduced the instrument is always liable to go wrong the next day, and it seems to me more important to arrange the routine of the testing station in such a way that any error is quickly detected. One of the ways in which we attempt to ensure that is by making it a rule that, when the examiner calls, the wattmeter which is provided for his use shall not be the instrument which has been used for testing the meters previously.

The author refers to rotating substandards or, as he prefers to call them, working standards. To describe a meter as a rotating meter is not quite accurate, because it is only the disc which rotates.

As regards automatic load control, mentioned on page 202, I was using a load-control device at Manchester over 25 years ago. It relied upon contacts, and has been in fairly continuous use ever since those days. It is interesting to notice that in the C.E.B. North-Western Area testing station an automatic control device is used consisting of a mirror on the wattmeter and a lamp which shines on to light-sensitive cells and holds the load quite steady. It is working very satisfactorily, and is an improvement on the American arrangement because it employs a standard wattmeter whose accuracy is in no way interfered with.

Do the costs shown on page 205 include the expenses of the clerical organization which must be required to deal with the forms that have to be filled up?

Are the personnel who handle meters in America thoroughly trained technical men, or are they what one might describe as semi-skilled technicians?

Mr. F. Seddon: I note with interest that although the permissible limits of accuracy in America are generally much closer than the legal limits in force in this country, there appears to be no organization for ensuring that these limits are adhered to. The State Commissioners apparently do not employ meter examiners, and the accuracy of the meters depends to a large extent on the integrity of the testers who fill in the very detailed test-report forms shown on page 204.

The system is open to criticism, and does not appear to be so effective as the method employed by our Electricity Commissioners for the check testing of a percentage of the meters submitted for certification.

The plug-in type of meter described does not appear to be of much advantage in America, since the meters are repaired and re-tested on site, but if adopted here it would help considerably towards reducing the cost of periodically changing meters in service. It would, furthermore, enable service connecting cables to be totally enclosed in conduit, and would thus dispose of the present anomaly of the service position being the worst part of the electrical installation.

Co-operation between meter manufacturers is essential if a standardized method of fixing meters is to be adopted, and meter manufacturers in this country appear to have something to learn from American manufacturers in this respect.

The universal use of credit meters in America considerably simplifies the problems of their meter engineers, but the progress made in domestic electrification in this country could not, I think, have been achieved without the use of the prepayment meter.

The information which the author gives regarding testing costs is interesting, but it is not clear as to whether the figures quoted are a direct evaluation of dollars at the present rate of exchange, or whether the difference in the cost of living in this country and the U.S.A. has been taken into account. The quoted figure of £9 per week would certainly be considered high remuneration for a meter tester in this country.

The electronic device described as being used for load-controlling on benches employed for testing rotating substandards could, I think, be adapted for controlling the voltage of the incoming mains supply to testing departments. Such a device would be of considerable use, and it appears to possess many advantages over the controlled-voltage motor-generator sets at present used.

I gather that the American supply undertakings are adopting the logarithmic type of maximum-demand indicator, shown in Fig. 17, in preference to the straight-line-characteristic type of demand indicator favoured in this country. A thermal demand curve may be desirable for the measurement of demand charges, but its application in this country would necessitate alterations in the existing agreements between supply undertakings and their consumers.

Mr. C. W. Hughes: America is evidently ahead of us in the matter of organization, and in this connection the reduction in the number of types and sizes of meters has been of great advantage to her.

It seems to me that there is room in this country for two very big movements: (1) to standardize the type of meter and thus reduce the number of types; (2) to reduce the number of test rooms and standardize the methods of testing.

An outstanding feature of the paper is the statement made about the close limits of accuracy to which American meter engineers work. If American meters are set initially to an absolute accuracy within an error band of 2 %, then I must admit that we cannot do as well in this country. There are, however, two points which are not consistent with this claim. First, on page 202 it is stated that a difference of 1 % may be allowed between consecutive tests on a meter; but if one is only allowing 2 % tolerance altogether a 1 % difference between tests seems to be inadmissible. Secondly, on page 200 there is the statement that one is allowed to use a wattmeter which has an error of 1 % on full-scale reading (i.e. 2 % on half scale) without applying any corrections; and yet it is still hoped that the meter will be accurate within 2 %.

While American engineers specify very narrow limits of error for the " as left " tests, the " as found " results may differ widely from true accuracy and yet still be within the legal limits. In New York it is apparently possible to have a meter 2 % slow on full load and 10 % fast on 1/10th load and still be within the legal limits, if one takes true account of the sign of the inaccuracy when working out " weighted average " accuracy. That seems to indicate a much worse position than exists in this country, where we have the same legal limits for " as found " and " as left " accuracy. Seeing that the legal limits must have some relation to the meters available and to the general practice in a country, it would appear that in the past the American people have been ahead of us in electrical design, and have thus been able to work to narrow initial accuracies, but that we have been ahead of them in mechanical design and workmanship and so have been able to obtain a much greater degree of maintained accuracy. The maintenance of accuracy is much more important than high initial accuracy.

The author points out that most American testing is done on site and so trouble due to transport of meters after testing is largely avoided; but I should not like to put too much faith in a rotating substandard which visits 14 or 15 different premises each day and is checked, as the regulations say it must be, only at the end of every fortnight. I think the Americans have had to specify close initial limits of error because they know they are only apparent limits.

Mr. G. Tilstone: Having made the same U.S.A. tour as the author has, I can confirm that the paper gives a very good survey of American metering practice. I would refer to the frank and open manner in which our American friends will discuss their problems and endeavours with a visitor—particularly if he happens to be an Englishman.

I notice that the author omits to mention the general question of ventilation of American meter departments. Air conditioning is in more general use in America than it is here because they have greater need for it, but in my opinion we should see more of it here if the advantages were more generally realized.

There are some ingenious methods of applying impulses from a standard clock for timing purposes. In one system a paper tape moving at a fixed speed has two records printed on it simultaneously; one record is of the seconds impulses transmitted by the clock, and the other record is produced by the stopping holes in the disc of the meter under test passing through a beam of light. This beam is focused on a photo-electric cell, and the output of this, after amplification, operates the printing unit. As the two records are printed simultaneously a variation in the speed of the tape affects both records equally and produces no error in the final result.

Mr. L. B. S. Golds has already described* to this Section an arrangement fitted to a standard clock to enable it to keep a circuit closed for a definite time. From the point of view of simplicity and universal application Mr. Golds's arrangement has much to recommend it. I am aware that a contact and relay are embodied, but I do not think that either should give any trouble, and if any comparison is necessary it should be remembered that all the other systems rely upon a relay of some kind or other. The simple and reliable timer described by Mr. Golds strikes me as superior to any I saw in the United States.

Under the heading of " Costs " the author quotes the cost per meter solely on the basis of direct wages paid. It would be interesting to know the percentages to be added to cover the overhead expenses of buildings, plant, and supervision, for an average-size undertaking.

I am glad that the author went to the United States to study their metering problems and methods, and I should like to think that in the near future we may have a visit from an American meter engineer for the same purpose.

Mr. H. S. Petch: It would be interesting to know whether America has any small utility companies, judged by British standards, and whether their level of equipment and work is as high as in the large ones.

Is there in America any recognized training system for meter department staff, and are particular qualifications insisted upon?

The co-operation between manufacturers, which the author mentions, is admirable. Has he any knowledge of how this came about? Was it a voluntary movement on the manufacturers' part, or was it a result of pressure from meter users?

Who is responsible in American utilities for the choice of meters—engineers or buying departments?

Are the American Regulations applied in a rigorous manner, or in a spirit of intelligent give and take? Are there penalties for non-compliance?

The author states that he is under the impression that phantom-load testing is not used in this country, except for large installations. In this connection it may be of interest to record that some 5 years ago we made up a single-phase unit of this type with a quick-connection device. This has been of very great value. With it, two men can easily site-test 10 meters per day, and the complete apparatus weighs about 8 lb. per man.

Site testing, if carried out at regular intervals on particular meters, can give much useful data as to the relative economic service life of various types of meter.

The author does not mention the so-called " long range " meter. He does state, however, that for testing purposes " heavy load " is taken as 60 %–100 % load, which presumably means 60 %–100 % current rating.

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* *Journal I.E.E.*, 1938, **82**, p. 423.

Some amplification of this question of rating of meters in America would be interesting.

Mr. J. L. Ferns: The paper does not emphasize that the reason why American metering practice is in some respects better than ours is that four conditions obtain in the U.S.A. which are not met with here. The first is prestige, the second is interchange of ideas, the third is proper representation, and the fourth is a unified tariff policy.

Taking the first point, there are, for instance, too many English undertakings which have no pride in their service board and the articles they put on it. As regards the second point, no encouragement is given to the meter superintendents in this country to get together to discuss problems and formulate results. Nearly all the work of this type that is done in this country is done by very public-spirited meter engineers, who are prepared to do it in their own time. Turning to the third item, American meter engineers can usually get together, have a conference, and transmit their desires to the managements, which in consequence receive a proper report on which they can act in unison. My experience is that in this country far too many decisions involving the entire meter industry are taken without due consideration of the practical engineer's requirements. Finally, dealing with the fourth item, tariff policy, what is lacking in the supply industry of this country is leadership and co-ordination, with the result that metering is often complex and shows a great diversity of method as between different undertakings.

If in Great Britain more attention were paid to these four points I think the general level of metering practice in this country would rapidly become higher than that obtaining in the U.S.A.

Mr. A. M. Strickland: Reference is made in the paper to the time for which meters can remain in service and to the intervals between on-site testing visits. Did the author find any means used for estimating such periods from results obtained on sample meters or otherwise; or, since the States Commissioners decide the between-test interval, do U.S.A. engineers rely entirely on their decisions?

The author makes the surprising statement that on-site testing brings the employees too much into contact with consumers. I thought, however, that the American utility companies encouraged such contact and found it beneficial.

The idea of checking the meter 60 days after installation is a good one, and it is interesting to find that many Continental supply undertakings insist on it.

Has the author found any evidence of detrimental results, over a long period, due to the solutions used in the chemical cleaning method? Can the more dangerous of the chemicals be removed successfully, or does any trouble result? I ask this since (contrary to the impression given in the paper) I understand that U.S.A. engineers have used chemical cleaners longer and more intensively than we have.

The author refers to the " as found " accuracy test; I should like to submit that, using the proper methods, one could at quite a low cost make abbreviated off-circuit tests on any meter on which a fairly large reading was indicated, and so get the information required. It would be interesting to know whether the author thinks this method would be adopted in America if it were decided to recall meters periodically from service for test.

Did the American meter engineers themselves decide which few types of meters were to be standardized, and do they still have a voice in this matter? It is interesting to find that an " A " type meter can easily be converted into an " S " type. That is certainly a factor in its favour.

If we decide to use socket-type meters we should, I think, consider adopting the American one as the standard, because it has got over its " teething " troubles.

The author's outline of the great amount of on-site testing which is carried out indicates why in the U.S.A. such good portable test meters were developed even some years ago. That such meters are very good I can state from experience. They must be used in large numbers, and perhaps the author would comment on this aspect.

Mr. A. E. Quenzer: A copy of this paper should be placed in the hands of the chief engineer and the meter engineer of every supply undertaking in this country. It is especially important that the former should read it, for without the backing of the chief engineers the meter departments stand a very poor chance of developing and progressing in the manner outlined by various Commissions in the U.S.A. Two of the greatest drawbacks in the past have been lack of finance and lack of interest on the part of higher officials in the supply undertakings. Although efficiency does not necessarily mean increase in cost, the question resolved itself into how cheaply the meter department could be run, with the minimum of personnel and equipment.

I am very interested in the New York Commission Regulations (page 200). There appears to be one omission, however, as regards the equipment required for a standardizing laboratory; surely timing apparatus should have been included.

Dealing with the section headed " Portable test standards," the frequency of checking of these standards and also of indicating instruments is excellent. I feel that the whole basis of accurate testing and the maintenance of such accuracy, apart from the standardizing equipment, can be summed up in the constant and frequent checking of substandards. I note that portable indicating instruments are checked at least once a week, and that the error must not exceed 1 % of full-scale deflection. Is not this figure rather on the high side? Nevertheless, the size of the error is not so important as the stability of the error.

On page 196 the author mentions the Continental influence in regard to size of meters; I take it that he means by this a decrease in dimensions. Surely there is a limit to how far one can go in this direction.

Regarding records, there is an opportunity for the Electricity Commissioners to give a lead in this matter, especially to the smaller undertakings. An attempt could be made to standardize card systems for all departments —such a step should simplify inspection work.

Mr. O. K. Coleman (U.S.A.) (*communicated*): In regard to expenditure (page 196), I think that all our meter departments are fairly well lighted, but unfortunately some of them are not spacious enough and in some cases expenditure is definitely restricted. We believe, however, that nearly all meter departments in the United

States are provided with the essential equipment and that fairly comparable results are obtained in all cases.

The author mentions on page 196 that one of the disadvantages of retesting on site is that it brings a large number of employees in direct contact with the consumer. Whilst I am inclined to agree with him, I would point out that a number of companies feel that such contact with the consumer is an advantage. There is also a general impression that the consumer feels more content when his meter is tested and left intact, than if it were changed.

In regard to the servicing of outdoor meters, although we have several hundred thousand meters installed outdoors, we have had no serious trouble in servicing and retesting, and climatic conditions have not, so far as we have been able to tell, produced any insurmountable difficulties in connection with bearings. Even along the Atlantic seacoast under the most adverse climatic conditions we have had no serious trouble with bearings and all types have been used, standard pivots, standard ball bearings and stainless steel bearings. We base our conclusions on the " as found " results of periodic tests and the number of bearings it is necessary to replace. There is, however, a problem in testing in inclement weather, and there is a great deal to be said for shop testing. We have already tried out tentatively, and now have under construction, two complete meter-testing laboratories mounted in a truck trailer.

The author states on page 198 that the loss of revenue over the whole country due to energy diversion is of the order of 5 %. Diversion can be due either to tampering or to improper metering. In the latter cases only a small part of the energy is diverted and I am sure that the total energy-diversion is well under 1 %. Even this, of course, represents appreciable revenue.

On the same page the author notes that " as found " accuracy applies to tests on site before adjustment, to disputed meters or to complaint tests. In this case " as found " accuracies are reported for all meters that are in service or have been in service, whether on site or in the laboratory, and most Commissions require a report of the " as found " accuracy of all meters tested on the periodic schedule. It is also mentioned that one of the Commissions states that it is not the intent of the rule that meters may be deliberately set in error by the amount of the tolerance. I should like to amplify this to the effect that while only one or two Commissions make such a statement in their requirements, it is the universal practice here to adjust all meters as close to 100 % as practicable and in no cases to our knowledge has advantage been deliberately taken of the tolerance.

In connection with " Tests " (page 201) I would point out that most of the regulations are based on meter ratings and that our meters have a carrying capacity considerably in excess of the ratings.

The author believes (see page 205) that although the ball type of bearing gives longer life, it has a tendency to be noisy and requires levelling. Approximately one-third of our meters are of the ball-bearing type, and we have never found it necessary to take more care in replacing such meters than with the pivot type, nor have we had any trouble that could be attributed to the bearings.

In regard to " polyphase metering " (page 207), only two American manufacturers, namely the General Electric Co. and the Duncan Electric Co., use the laminated disc. The Sangamo Electric Co. use a solid disc and eliminate interference between elements by a shield. The Westinghouse Co. in their small-type polyphase meter use two discs directly adjacent to each other, with one electrical element mounted above the top disc and the other below the bottom disc. Such a meter is illustrated on page 206 of the paper.

Mr. F. C. Holtz (U.S.A.) (*communicated*): The smaller utilities in the United States are generally under the control and guidance of the larger utilities, who have pretty well standardized methods throughout all their territories. For example, there is the Commonwealth and Southern Group, which has under its jurisdiction and control the Consumer's Power Co. in Michigan and a number of properties in Tennessee and Georgia. All these meter departments are under the control of one engineer and the smallest operating unit follows precisely the same practice as the larger one in regard to meter testing. If they do not have sufficient equipment, such as potentiometers, they are frequently supplied with properly calibrated portable test standards and in a manner similar to that accomplished under the Electricity Supply (Meters) Act carry on the relatively high-grade job of testing.

There is a growing feeling in the United States in favour of the laboratory method of testing meters. This is brought about by the frequency with which bad weather is encountered, although some meter engineers feel that outdoor metering does not necessarily promote this tendency.

Mr. G. F. Shotter (*in reply*): In the discussion some points have been mentioned by more than one speaker. Briefly, these concern (*a*) methods of ensuring that the American regulations are observed, (*b*) personnel, and (*c*) costs. These questions are of a general nature and I propose to deal with them after answering other points raised in the discussion.

Mr. Hill asks how American meter manufacturers manage to discourage internal competition. The firms compete among themselves, but co-operation between them seems to be much more marked than it is between similar firms in this country. Also, the firms appear to be so well established and their designs of meters are considered to be so good that any newcomer in the meter market would probably have an extremely difficult task to compete with them.

Mr. Hill's impression that a meter of the plug-in type could be removed and a diversion device surreptitiously inserted and the meter replaced, is not quite correct, for the meters are very effectively protected by " armour clad " housings or bases. No particular advantages are claimed in the paper for plug-in type meters, the main reasons for their use in outdoor installations being to prevent pilfering and for the convenience of the meter readers and testers. The standardization of meter bases by all manufacturers is, however, a useful feature.

I agree with Mr. Hill's remarks in regard to the American method of calculating the " as found " average error, but, as stated in the paper (see page 199), the real difficulty in computing the actual error arises if the meter has a widely divergent curve and it is increased if the meter is operating over a wide range of loads. I also mentioned the use of a suitable check meter.

With reference to the American method of determining "creep," Mr. Hill seems to have lost sight of the fact that the speed of "creep" is related to the full-load speed and is independent of the rating of the meter.

I do not agree with Mr. Hill that the reason why the dial testing method is not used in the United States is that American meters are not provided with testing dials. The rate method of testing is apparently considered to be more satisfactory. On the other hand, it can be said that the reason why British meters incorporate six small dials is that certain engineers in this country insist on the dial method of testing. There is, however, much to be said for the four large dials reading in units and multiples of units used in America.

Recent reports indicate that the balance of opinion in America is swinging in favour of the ball-type bearing, which is considered in many quarters to be better than the pivot type. A secondary advantage is that such bearings can be used without oil.

Mr. Hill asks why prepayment meters cannot be used in the United States. The main reason is possibly "diversion," and no doubt American supply companies are extremely reluctant to add another source of trouble to those already existing by presenting pilferers with a fruitful medium for exercising their talents. Prepayment meters are also unsuitable for outdoor installations.

In reply to Mr. Richards, site testing apparently suits American requirements best. I did not investigate very closely the question of meter transport but, to the best of my knowledge, vans are used for this purpose.

I agree with Mr. Howarth that accuracy can be achieved without additional regulations under the Electricity Supply (Meters) Act. The periodic return of meters for servicing, however, is an important point.

The word "extravagance" in connection with American expenditure is not mentioned in the paper, and I think that American engineers consider their expenditure to be justified. I would refer Mr. Howarth to Mr. Coleman's communication on this point.

Testing on site in America has been evolved from the early days, but it has certainly been carefully planned.

Mr. Howarth and I still disagree on the question of the 6 months' period between tests on laboratory instruments. In my view the period depends upon the instrument and its use, and I think the American requirement of tests every 3 months has much to be said for it.

In connection with Mr. Howarth's comment on my reference to "rotating" substandards, I would point out that the official description given in the Meters Act is "substandard rotating meter." I agree that the description is, to the pedantic mind, inaccurate. As a matter of interest, the word "substandard" now means in the United States inferior quality.

I am pleased to learn that Mr. Howarth used a load-control device at Manchester over 25 years ago.

I do not agree with Mr. Seddon that the plug-in type meter is apparently of little advantage in America. I have already mentioned "diversion," outdoor installations and the convenience of meter readers, and I think Mr. Seddon's remarks regarding convenience in servicing apply equally well in the United States. In regard to installation arrangements, I should like to draw attention to the battery of meters shown in Fig. 16 (Plate 3). It may also interest Mr. Seddon to know that outdoor metering is used considerably in Australia.

I endorse Mr. Seddon's remark that our meter manufacturers have something to learn from American manufacturers in regard to co-operation, and I also agree with him regarding the uses of credit and prepayment meters.

Mr. Hughes raises a very interesting point in regard to the close limits of accuracy specified in the New York regulations. He will agree, however, that it is possible to have a 1 % error between two consecutive tests on a meter and still keep within the accuracy stipulated. In my view, however, the limits are rather fine and, as I stated on page 199 of the paper, the effect of the New York regulations is to penalize the utilities, because in order to comply they have to set their meters, on an average, approximately 1 % slow.

Mr. Hughes also refers to the use of a wattmeter having an error of 1 % of full-scale deflection (i.e. 2 % on half scale) without applying any corrections for the testing of meters within 2 %. This is not quite correct, since the regulations state that all portable test standards used for testing watt-hour meters must be provided with a calibration certificate.

Mr. Hughes is hardly justified in citing a meter 2 % slow on full load and 10 % fast on 1/10th load as within the American legal limits for "as found" accuracy. In my view this argument has little relation to actual experience, and I think that the error in the meter envisaged by Mr. Hughes would be nearer 10 % slow at 1/10th load. In any case, my impression of American engineers is that they would be perfectly capable of dealing with any problems of this nature. Again, I entirely disagree with Mr. Hughes on the point of meter design, and I think that it is an acknowledged fact that both the electrical and the mechanical design of American meters is of a very high standard.

I am glad that Mr. Tilstone mentioned air-conditioning, a point which I omitted to include in the paper. This is yet another refinement which the best American laboratories can claim, although, as Mr. Tilstone says, they probably have more need for it than we have.

Mr. Petch's question as to the standard of equipment and work in the smaller utilities is best answered by Mr. Holtz's communication.

Co-operation between American manufacturers and users must vary in individual cases, as it does in this country. So far as I am aware, American engineers are responsible for the choice of meters.

Although I did not mention in the paper long-range meters, this type capable of an accuracy of ± 1 % has been used in America for some time. I understand that the range of these meters has been extended with an even better performance up to 400 % full load, and with a thermal capacity supporting such a rating.

While Mr. Ferns's comments are of interest, I think they raise issues a little beyond the scope of the paper and I do not feel capable of replying satisfactorily to them.

In reply to Mr. Strickland, I have no actual evidence regarding the fixing of the time period for the return of meters from service, but I think that the period was arrived at as the result of experience. Mr. Strickland will be interested to find in Mr. Coleman's communication partial confirmation of his comment in regard to the American viewpoint and contact between outside testers and consumers.

I did not intend to give the impression that American engineers have not long used chemical methods of cleaning; in fact my intention was quite the opposite. I do not think that trouble results from their methods, which appear to be very successful.

In regard to the standardization of types of meters, if Mr. Strickland means the plug-in type I understand that the development of this type of meter coincided with the evolution of a standardization programme of the utilities, which had as its object uniform specifications for meter installations for both indoor and outdoor use.

I should like to endorse Mr. Strickland's high opinion of American portable test meters: I think that in the past their types have been far in advance of British types.

I agree with Mr. Quenzer that timing apparatus should have been included in the New York regulations. The laboratories are provided with standard clocks.

I am glad to learn from Mr. Coleman's communication that the percentage of energy diversion is probably much smaller than that stated in the paper. My figure of 5 % was obtained from an official document published by the Edison Electric Institute.

Turning now to the points of a general nature raised by several speakers, I should like to deal with the question of the official methods for ensuring that the American regulations are observed.

Early in the paper I mentioned that it was evident that American engineers have had, and still have, a real appreciation of the necessity for maintaining a high standard of accuracy. Also I stated that the American regulations under review were much more comprehensive than our own, and that they had been in force much longer. It seems obvious to me that the American Commissions would hardly prepare such elaborate and strict regulations, covering standards of accuracy, equipment, rules for testing and servicing, and even illustrating official forms, etc., if they had not taken adequate measures for ensuring that their stipulations were observed.

It will be noted that under the New York Commission regulations (see page 200) a laboratory shall not be deemed properly equipped until it shall have been inspected and shall have received a certificate of approval from the Commission.

Again, under " Tests " (page 201) it will be noted that a referee test is made or witnessed by representatives of the Public Service Commission.

Official forms reporting all tests have to be filed with the Commission each month (see page 202) and, so far as I know, the Commission's inspectors can call upon the utilities at any time to make checks. These forms have to be submitted for all tests, whether in the laboratory or on site (see Mr. Coleman's communication).

Under the heading "Reference standards" (page 200), mention is also made of the Commission's laboratory, which presumably would not be maintained for the sake of appearances.

I trust that these explanations will satisfy those speakers who have raised questions in regard to methods for ensuring that the American regulations are observed.

In regard to personnel, it was obvious to me that the staffs in the respective sections of the meter departments were highly efficient and were perfectly capable of carrying out their particular duties.

On the subject of costs I have little to add to the information already given. The "cost per meter" figures quoted in the paper include, so far as I know, overheads. They were worked out at the rate of exchange obtaining at the time of writing the paper and they do not include the " cost of living factor," whatever that may be. As mentioned in the paper, I do not think it is possible to make any precise comparison, although the figures do give some indication of relative costs.

NORTH MIDLAND CENTRE, AT LEEDS, 30TH MARCH, 1940

Mr. J. Bryce: It would appear that the Americans have brought their metering practice to a fine art, and the paper rather serves to show the defects in our own practice. One must remember, however, that the American supply companies are considerably greater than any of the British undertakings. For example, our largest undertakings handle between 300 000 and 350 000 meters, whereas the Consolidated Edison Co., New York, deals with 3 million meters. The photographs on Plates 1, 2 and 3 show that considerable attention and capital have been devoted to the provision of buildings and electrical equipment suitable for the use of meter departments; such an outlay in this country would only be justified, if not achieved, for the largest of our undertakings. We have some 600 authorized undertakings in Britain, a country smaller than many of the American States, and it is hardly to be expected that the smaller undertakings can compare with the larger ones in matters of standardizing equipment, test gear and building accommodation.

Whereas in the U.S.A. there are only four meter manufacturing companies, in this country there are probably between 15 and 20 manufacturers producing some 50 different types of meter, and it is the work of our meter engineers to get these certified. The production of meters is greatly simplified by adhering to standard dimensions, terminal arrangements, etc.

I notice that the temperature-compensated meter has been used for many years in America; its development in this country has recently been accelerated, mainly by the Meters Act of 1936. There is much to be said for meters of ample design as compared with " Continental " patterns. When manufacturers compete rather than co-operate with one another, meter dimensions are reduced, and often the result is an inferior product.

It is largely a matter of opinion and convenience whether meters are tested on site or in the laboratory. In America, where supply areas cover perhaps many hundreds of square miles, on-site testing is probably more convenient than laboratory testing.

It would appear that fraudulent diversion of energy has been mainly responsible for the introduction of the ironclad meter, yet it presents a rather neat appearance and might be widely used in this country. The advantage of outdoor meter installations is obvious, and it is a pity that too little attention is given to this matter in our country. For the sake of convenience and minimum expense, meters are often fixed in larders, coal cellars, outside bedroom doors or on wet walls. It would be a distinct advantage if all meters were fixed above ground-level and in dry places.

I am surprised that two accuracies are stipulated by the American Regulations, namely "As left" accuracy and "As found" accuracy. For example, if the accuracy of a meter were disputed after it had been, say, 3 weeks in service and the "as found" figure were found to differ by 3 % from the "as left" figure, would one assume that the "as left" figure was of doubtful value? The difference in errors chosen for this particular example may appear rather severe, yet it is a possibility that has to be reckoned with in practice.

I do not agree with the author's statement "Our tolerances which apply to laboratory tests are somewhat liberal." When I contrast the various types of meters produced in this country with the well-designed American products, and remember that we have only one standard of accuracy for the "as left" and "as found" tests, from 5 % to 125 % of full load, I do not think that our tolerances are too liberal.

I am rather surprised that the American standardizing laboratory equipment includes, amongst other items, only "one potentiometer of precision type." For companies handling such large quantities of meters, one would expect the regulations to stipulate the inclusion of two potentiometers. The provision of one set of standard resistors and one standard cell held in reserve for reference purposes only, is a desirable feature, but surely a potentiometer is liable to error which cannot always be detected unless it is compared with another potentiometer, or standardized by the supreme authority.

It is interesting to note that before American standardizing laboratories are deemed to be properly equipped, they must receive a certificate of approval from the Commission. It is a pity that in this country we do not certify the efficiency of the personnel as well. Meters, instruments and standardizing equipment can sometimes lead to doubtful results when handled by inexperienced operators. The Meters Act of 1936 cannot be completely successful unless trained meter mechanics and testing assistants are employed in our meter departments. Before the Act came into force almost anyone could be termed a meter tester, provided he could use a screwdriver and check the speed of a meter disc.

The regulation with regard to "creep" is somewhat to the consumer's disadvantage. A meter disc may take as long as 8 minutes to "creep" one revolution, and this can lead to considerable error in registration, particularly with the small consumer.

Method "A" in our regulations is not used in America, where the dials are checked by either mechanical or electrical means. I should be glad if the author could explain what particular electrical means are adopted for this purpose.

The automatic load controller developed by the Consolidated Edison Co., New York, is of special interest. It is stated that the controller holds the load steady within 0·05 % with the supply taken from the mains, but it is not clear to what extent of variation in mains voltage the load controller can be relied upon to give the accuracy stated.

Miscroscopic examination of pivots and jewels is apparently a routine matter in the United States, but not in this country. Before our Electricity Supply (Meters) Act, 1936, came into force, microscopes were regarded by many meter engineers as a luxury rather than a necessity. Since most of our certification difficulties are due to defective meter bearings, microscopic examination of pivots and jewels is very necessary if reliable results are to be achieved.

In order to compete with the American supply companies we in this country should have to amalgamate our meter departments—i.e. have a central meter department catering for some 20–30 undertakings. This change would naturally lead to much opposition, although it would make possible far greater efficiency. If the meter manufacturers would decide on some standard pattern of meter, and one of robust design, matters would be greatly simplified. Personally, I would rather work to overall limits of error of 2 % on a first-class meter, than to tolerances of 6 % on inferior types.

Mr. A. C. Bailey: I am surprised to learn that there are only four manufacturers of meters in the United States. This limitation means that there can be close co-operation between them, and thus the selling price of the meter can be kept up, but, on the other hand, a better meter can be produced than is possible if there is very keen competition.

The author does not mention much about the cost of testing meters. I imagine that the palatial testing stations illustrated in the paper will involve high overhead costs as compared with the labour costs, on account of the high charges for interest on capital. In this country, generally speaking, one finds that the overhead costs are equal to or a little greater than the labour costs. Probably in the U.S.A. the overhead costs are 5 times as great.

I agree with the author in deprecating on-site servicing, which appears to be the usual practice in America. I feel sure that it is impossible to service a meter efficiently under the climatic conditions which frequently prevail in the U.S.A. Again, on-site servicing seems most contradictory when elaborate and palatial testing stations are apparently thought to be justified for the initial testing of meters.

I do not consider that outdoor metering installations are the best means of countering the frauds perpetrated by American consumers; surely the proper answer is to have a well-protected indoor installation. If a consumer is apt to be fraudulent and he has an outdoor meter it is easy for him to damage it and then disclaim responsibility for the damage on the grounds that it occurred outside his premises. My own undertaking, like the author's, is very little troubled by meter frauds.

Table 1 rather suggests that the Americans test to a much greater order of accuracy than we do in this country, but it should be remembered that they only test the meter down to 1/10th load, whereas practically all the troubles are met with between 1/10th load and 1/20th load.

I am impressed by many of the New York State Commission's Regulations regarding standard and substandard instruments, but I do not like the part of Section (27) which refers to " creep " (see page 202). For instance, a 20-ampere meter which has a constant of 240 revolutions per kilowatt-hour can record 8 units per week with a (legitimate) forward " creep " of 1 revolution in $5\frac{1}{4}$ min. Most of the consumers in our country would object to the extra charge which this would entail. I much prefer our own recognized method of " creep " determination.

The author mentions that a rotating cleaning machine using chemicals for cleaning clockwork is used on several of the undertakings in America. The use of such machines in this country has become quite common, and they give exceedingly good service.

I do not agree with the author that a noisy meter is of no consequence if the meter forms part of an outdoor installation. If there is noise it means that excessive wear will take place, and this of course is of great consequence.

I like the American idea of using a cumulative demand attachment for important metering. By means of such a meter it is no doubt possible to show whether an error has been made in reading and whether there has been any attempt to alter the demand-indicator reading.

Generally speaking, I feel the American methods are no better than the methods employed in our own country, but we have a lot to learn from America regarding the upkeep of standard equipment.

Mr. L. C. Bunce: I agree with Mr. Bailey that, in general, American meter-testing practice is little better than our own. The essential difference arises from the fact that it is more advantageous to us, with our small undertakings, to test meters in local testing stations rather than to test them on site.

I should be pleased to learn how the American meters are certified, as it would seem to be very difficult for an examiner to travel many miles for the purpose of testing meters on site. I am pleased to learn that the larger meters, especially those over 100 kW capacity, are tested more frequently than our own.

Can the author give any information regarding the method used for testing 3-phase voltage transformers, and as to how the difficulty was overcome of unequal loading of the phases of this type of transformer?

I feel that in this country not enough attention is paid to the problem of allowing for the voltage-transformer errors. In far too many cases the test-results obtained on the voltage transformers at unity power-factor burden are used, and due cognizance is not taken of the fact that the meter burden on the transformer has a power factor of the order of 0·2 lagging. I have found that the errors of voltage transformers, and phase-angle errors in particular, become quite large when calculated for low-burden power factor.

The author has little to say about kVA measurement, and I should welcome any information regarding this side of metering in America. Summation metering also is a subject which is not mentioned in the paper, and I should be interested to learn which system enjoys the greater popularity, the current-summation or the impulse-summation system.

Mr. K. C. Coop: The paper would have been of greater value had the author gone into more detail with regard to the methods applied to on-site testing. He refers on page 202 to the fact that tests on site are carried out by means of portable rotating induction-type substandards and " artificial " loads. The artificial load may either be provided by the meter tester himself or consist of the whole or portions of the connected load. If, in the first case, the tester has to supply his own resistors and reactors, then the apparatus must necessarily be comparatively bulky. If, on the other hand, he uses the installed apparatus as the artificial load, then I should imagine it is difficult to obtain the required range of loads, particularly if he wishes to carry out tests on a lagging power factor.

Mr. E. S. Bolton: I think there is something to be said for on-site testing if one takes into consideration the short period of a year or two and the cost of connecting new meters and of disconnecting the old. One has to take into account the cost of transport and wages, which in this country are fairly high to-day, and one has also to decide on the period of service to be allowed between overhauls at a testing laboratory. In cases of short-period testing I do not think there will be any serious faults on the meter which cannot be adjusted after a rough test on site.

I should like to have more information about the meter bearings and the various types of jewels used in America, and also about the life of the jewels. I have noticed that on some of the jewels which we use in meter work a rough or cracked surface forms very soon after the meter has been installed.

Mr. W. T. J. Atkins: I notice that in the circuit of the electronic current regulator shown in Fig. 9 there are two connections leading to an automatic timer. Apparently the scheme of operation is to switch on the voltage circuits of the meters which are being calibrated, and to switch them off at the end of a measured interval of time, so that the meter discs start from rest and finish at rest. It seems to me that such a method introduces starting and stopping errors into the measurement, and I should like to know the author's views on the relative accuracy of this procedure as compared with the timing of an integral number of disc revolutions with a " running " start and stop.

I am unable to grasp the method of operation of the " cumulative demand attachment " referred to on page 207. I appreciate, of course, the desirability of retaining individual demand records; but the description given in the paper of this device is so condensed that it is not clear how the object is achieved.

[The author's reply to this discussion will be published later]

ELECTRIC CLOCKS*

By F. B. ATKINSON, B.Eng., Student.†

[ABSTRACT *of Paper read before the* MERSEY AND NORTH WALES (LIVERPOOL) STUDENTS' SECTION, 11*th April*, 1939.]

The applications of electricity to horology have been numerous, yet it will be found that any modern electric clock belongs, in first principles at least, to one or other of the following groups.

(1) THE IMPULSE SYSTEM

This system, in which a master clock or regulator is arranged to send out electrical impulses at short intervals—usually every half-minute—to operate a number of subsidiary or secondary dials, is met with in factories, railway stations, hospitals and other places where accurate time is required throughout. Besides being used to actuate clock dials, the impulses may be applied to operate workmen's time-recorders, and programme controllers, to control industrial processes, and for many other such applications.

The secondary clocks or dials, which are characterized by the fact that the hands usually move forward in jumps of a half-minute at a time, are all controlled from the master clock, to which an advance and retard device is usually fitted so that all the dials on the system may be adjusted together. This is especially valuable at the change-over from Greenwich to Summer Time or vice versa, and also for marine use, because as a ship sails eastward it is necessary to advance the clocks, and to retard them when sailing westward.

For marine use any form of pendulum master clock is, of course, out of the question, and balance-wheel control is used instead.

The impulse system is not extensively used in small private houses, as the cost per dial is high; also the additional wiring is often an objection.

All impulse clock systems comprise three essentials:—(*a*) A master clock arranged to transmit electrical impulses at regular intervals to the clock dials. (*b*) The dials or secondary clocks. (*c*) The battery or other source of power.

(a) The Master Clock, or Regulator

This is invariably a high-quality timekeeper, and may be either a mechanically wound clock or a mechanical clock which is wound electrically, fitted with suitable contacts which close at half-minute intervals; or it may be a purely electrical clock, as is almost universal practice to-day.

All modern master clocks and regulators, for land use, are fitted with pendulums having a swing of 1 sec. The pendulum bob, which may weigh from 10 to 15 lb., is made of cast iron or steel, and the pendulum rod of Invar or Sinevar, a nickel-steel alloy having a coefficient of expansion of 0·0000009 per degree Centigrade. The upward expansion of the bob almost exactly compensates for the slight downward expansion of the rod.

Purely electrical master clocks represent the simplest and most accurate type of clock. Modern designs rarely have more than one wheel, and the pendulum is as free as possible. This is very important, because to obtain absolutely accurate timekeeping the pendulum must not be called upon to do any mechanical work nor may its swing be interfered with in any way.

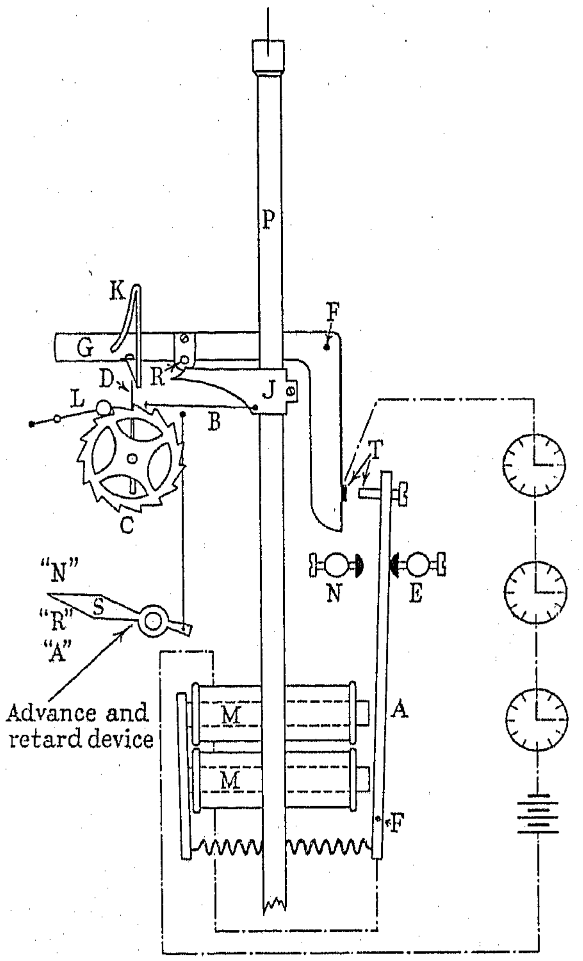

Fig. 1

A. Armature.
B. Click.
C. 15-tooth wheel.
D. Vane.
F. Pivot.
G. Gravity arm.
J. Impulse pallet.
K. Catch.
L. Back-stop.
M. Coil.
P. Pendulum.
T. Contacts.

In a mechanical clock the pendulum is bound up with the escapement mechanism, from which it receives an impulse at every stroke; so that the pendulum cannot be called "free," no matter how efficient the escapement.

In the commercial master clock (Fig. 1) of the Synchronome impulse-clock system, the only work the pendulum has to do is to turn a light " count " wheel to enable a pivoted " gravity arm " to be released every half-minute. The action of the gravity arm, as well as imparting an impulse to the pendulum to keep it swinging, causes a contact to be closed. The closing of this contact causes the secondary clocks to be advanced one step and the gravity arm to be replaced on its catch.

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* The original paper, of which this is an abstract, was awarded a Students' Premium by the Council.

† Lever Brothers (Port Sunlight), Ltd.

The gravity arm gives an impulse to the pendulum at the moment when it passes through the zero or central position. Thus the pendulum is free at all times except in the middle of its swing: not only is the escapement detached but it operates at zero, a combination which is ideal.

The commercial forms of electric impulse master clocks are capable of being regulated to within 1 sec. per week.

(b) The Secondary Clock

The standard type of secondary clock is simple in construction. If the impulses are received at half-minute intervals then the minute-hand spindle is fitted with a 120-tooth ratchet wheel and the necessary gear train to drive the other hand at 1 revolution in 12 hours. Adjacent to the 120-tooth wheel is an armature operated by an electromagnet, so arranged that each impulse advances the ratchet wheel one tooth and with it the long hand through 1 half-minute.

This type of secondary clock is robust but rather noisy, and for such places as hospitals, hotel bedrooms, etc., where the half-minute click or thump is objectionable, there is a special inaudible type of movement, which owes its silence to the fact that the armature does not strike a metallic stop when attracted by the magnet.

The standard dial movement is applicable to clocks up to 10 ft. in diameter; for larger or other dials having exposed hands a special type of movement is used. The basic principle of these special movements is that the clock hands are driven by a separate motor, controlled by the time impulses from the master clock.

(c) The Battery or Power Supply

This may consist of either primary cells or accumulators, or the clock system may be worked direct from the electricity supply mains. A good make of dry cell will run an installation for 2 or 3 years continuously, the shelf life of the cell being an important factor.

When accumulators are used, arrangements must be made for recharging, and when an a.c. supply is available trickle charging is nearly always employed.

Direct operation from the electricity supply mains is seldom used on land installations but is often met with on marine impulse-clock systems.

(2) SELF-CONTAINED ELECTRIC CLOCKS

A self-contained electric clock is one which is sold as an independent clock, its motive power being derived from a small battery actuating the pendulum directly.

Most clocks of this type are opposed to strict horological principles in that the pendulum is made to drive the clockwork instead of merely to control its rate. Great care has therefore to be taken in the design of these clocks to make them good timekeepers. Their chief advantage is the fact that they require no winding; but there is a defect in this merit, since they are apt to be neglected and allowed to run widely out of time.

The current consumption of these clocks is very small, being of the order of 2 to 3 milliamp. at the contact moment, and they will usually run for 2–3 years on a small $1\frac{1}{2}$-volt dry cell.

The clocks possess a certain fascination of their own, in that they are obviously electric and yet possess a "tick," like an ordinary clock.

(3) SYNCHRONOUS ALTERNATING-CURRENT MOTOR CLOCKS

This type of clock is one of the latest developments in electrical horology and is entirely different in principle from any other class of electric clock. It can only be worked from "time controlled" alternating-current mains, and the hands are driven, through suitable gearing, by means of a very small electric motor whose speed is entirely governed by the frequency of the supply. Since the advent of the grid, in which large generating stations are interconnected, the frequency of the supply over the whole country has been standardized at 50 cycles per sec., and means have to be used which maintain this value to a high degree of accuracy.

In actual practice the frequency is measured by comparison with a high-grade clock, and thus, although only a by-product as far as the supply authorities are concerned, a source of accurate time is available to all consumers connected to the grid.

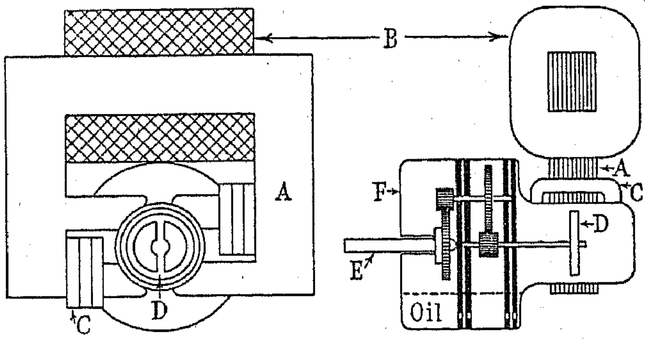


Fig. 2

A. Laminated core.
B. Coil.
C. Shading rings.
D. Steel disc.
E. Shaft.
F. Brass casing.

Synchronous-motor clocks are simple in construction, cheap to manufacture and very compact: there is no pendulum or balance-wheel, and consequently there is no regulating or levelling to be done. The moving parts are light and, in some makes, are sealed in an oil-filled compartment. No oiling is then necessary, and the clock runs very quietly.

Another point in favour of synchronous-motor clocks, especially for domestic use, is the fact that the hands move steadily forward and not in half-minute jumps as in impulse-type clocks.

Fig. 2 shows the motor of a self-starting high-speed type of synchronous clock, while Fig. 3 shows motors of the slow type of non-self-starting clocks. The former have the disadvantage that, if the supply is shut off for only a few minutes, all the clocks will be this amount slow, and the error may not be noticed. On the other hand, the non-self-starting type will stop altogether in such a case, and this will be quickly noticed.

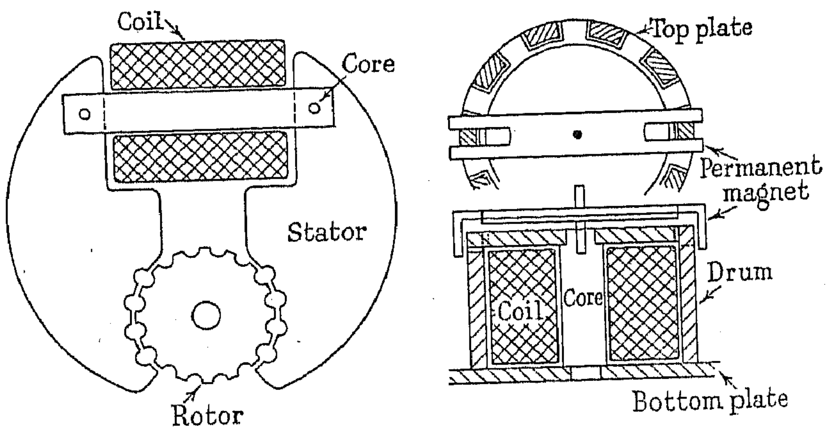
The power consumption of these clocks is small, varying from 3 to 5 watts according to size and make. They are usually permanently connected to the supply mains by a special connector.

(4) SYNCHRONIZED CLOCKS

Under this heading are included all those clocks, whether electrically or mechanically driven, which are arranged to be corrected at intervals by signals transmitted from a source of standard or substandard time.

Their principal field of application is as public clocks and the clocks of public service undertakings. To-day it is by no means common to fit an elaborate synchronizing gear, because the accuracy of the modern electric-clock installation is such that only occasional correction is necessary and this may be done manually by checking against the time signals of the B.B.C.

The source of standard time in this country is Greenwich, and Greenwich Mean Time is available for synchronizing and checking clocks in a number of ways. The regulators or clocks at Greenwich and at most of the principal observatories of the world are electric, being of the special type designed by Mr. W. H. Shortt, in which each regulator consists of two parts—the "free pendulum" and the " slave clock." The slave clock, which releases a gravity arm at definite intervals to keep the free pendulum in motion, is maintained in exact synchronization with the free pendulum by means of a " hit and miss " synchronizer. The impulses to the indicating dials are also despatched by this slave clock, and the free pendulum has nothing to do but to swing to keep time. The free pendulum is of Invar, and the whole of its mechanism is enclosed in an airtight case and exhausted of air to a pressure of about 1 in. of mercury.



Type "A"

Type "B"

Fig. 3

There are five of these Shortt clocks at Greenwich Observatory, two being used for Mean Time. The free pendulums are installed in a cellar clock chamber kept at a uniform temperature, while the slave clocks are situated on the ground floor in a convenient and accessible position. These clocks can be relied upon to keep time to within 1 sec. per year, and their accuracy is such that the clock indications are regarded as the constant quantity and the " clock star " observations as the variable one—a reversal of previous practice.

The standard time signal may be used for two methods of correction—forcible and gradual. With forcible correction, which does not attempt to alter the rate of a clock, the reception of the time signal causes the minute hand (or the " count " wheel in the case of impulse clocks) to be quickly drawn to the zero position. Gradual correction consists of the addition or subtraction of a small weight to or from the pendulum, according to whether the clock is slow or fast when the signal is received, thus altering the time of swing of the pendulum.

It is particularly necessary that time-recorder clocks, used in factories, should correspond with the general factory time. Since they incorporate considerably more mechanism and require more driving power than an ordinary clock, they are usually left as independent units, wound weekly, and a scheme of synchronization is applied to keep them in step with the general clocks. In this case the synchronizing signals comprise the half-minute impulses from the factory-time circuit instead of a signal from an outside source of standard time.

(5) ELECTRICALLY WOUND CLOCKS

These clocks rely on a pendulum or balance-wheel for their timekeeping and on a spring or weight for their driving motion, electricity being called upon to wind up the spring or weight. The winding is done at frequent intervals and is nearly always automatic.

The subject of electrically wound clocks includes domestic, turret and motor-car clocks, and time switches for controlling street lighting, shop-window displays, industrial processes, etc. Certain of these clocks have a reserve of several days' driving power in the event of failure of the electric supply, while others will only run for about an hour.

These clocks have the following advantages: (*a*) They require no winding. (*b*) Independence of interruptions of electric power supply. (*c*) They have a definite " tick," and the hands move steadily forward and not in half-minute jumps. (*d*) The winding motor can be suitable for either d.c. or a.c. supply, and with the latter the frequency need not be time-controlled.

The disadvantages of the electrically wound clock are:—(*a*) Being both a mechanical clock and an electric motor, it is more costly than either a mechanical clock of equal quality or a synchronous-motor clock. (*b*) The timekeeping is dependent upon individual construction and regulation, and there is no guarantee that a number of these clocks will indicate the same time.

As the power required to wind a clock is small, the efficiency of the winding motor or mechanism is of minor importance. Low first cost and robust construction are more desirable characteristics. Electromagnetic ratchet mechanisms and small single-phase copper-disc motors are used more frequently than the orthodox type of motor, which is only employed where the power required is relatively large.

DISCUSSION ON "METHODS OF MEASURING THE TORQUE OF INDUCTION MOTORS"*

Mr. G. Pember (*communicated*): The author hardly does justice to the brake-loading method of finding the torque/speed curve for an induction motor, and the curves which he shows in Figs. 1 and 2 should be capable of considerable extension. Difficulties of measurement in this method usually arise only when the pull-out torque is exceeded, as the motor then becomes unstable. Examination of the curves on pages 598 and 599, obtained by other methods, however, reveal that this critical point is not reached until the speed has dropped to about 0·7 in the single-cage, and to about 0·3 in the double-cage motor. One would expect, therefore, to see the brake-load curves plotted with considerable accuracy down to these speeds at least. Difficulty may be encountered with rotor heating in the double-cage machine at speeds below 0·9, but this may be overcome by allowing a light-load period for cooling between successive load readings, if it is not found possible to take all the readings consecutively without serious overheating.

With two operators to take readings it should be possible also to get a few points on the unstable part of the curve for the single-cage motor, to at least the accuracy of the author's motion-picture method. This would enable the curve to be traced completely from synchronism to standstill.

In his comparison of the methods of measuring torque the author states that the brake-load method " gives no data concerning regions of poor torque performance or the possibility of crawling." Since, however, this method very closely resembles the loading of an induction motor in service, this statement is equivalent to saying that such a motor cannot be observed to crawl under ordinary conditions of loading. A motor is said to crawl when it fails to accelerate its load up to normal running speed, but settles down steadily at a fraction, say one-seventh, of that speed. It is, thus, quite possible to start a motor from rest with different loads on the brake pulley and to find whether at any particular load it exhibits this stable crawling torque.

The rotational accelerometer (at 400 volts) and the motion-picture camera give curves which are very similar in shape. It would be interesting, therefore, to have further details as to why the former will reveal parasitic synchronous torques while the latter will not, since the camera is admittedly working with its greatest accuracy at low motor speeds.

The value of the paper would be enhanced if details were given of the accuracy with which the angles may be measured in the film records shown in Figs. 7 and 10, and hence if an estimate were made of the probable overall accuracy of the two camera methods.

Mr. A. C. W. Vincent Clarke (*in reply*): It was not intended to present a comparison with any but normal brake-load testing, as it is not felt that complete reliance can be placed on the results of such tests as are suggested by Mr. Pember. These tests were in fact attempted, and the difficulties encountered were due to heating and to inability to make the induction motor run reasonably stably unless the slope of the torque/speed curve was very definitely negative. Apart from heating, therefore, it was not possible to make reliable measurements at loads much in excess of normal.

It is not enough to avoid only serious overheating, since a relatively small degree of overheating can affect the torque figures appreciably, owing to increase of rotor resistance.

The brake-loading method will enable a severe case of poor torque/speed characteristic to be demonstrated by causing the motor actually to crawl; but in a case even as serious as that of the double-cage motor tested it was only possible to achieve this at reduced voltage.

Parasitic synchronous torques are not revealed by the motion picture camera because they vary at a frequency comparable with or greater than that of the 50 c./s. supply (see oscillograms). This is comparable with the taking rate of any but a high-speed camera.

The limit of accuracy of the motion-picture camera method is not easy to specify, as it depends upon both the taking rate and the accuracy with which angles may be measured, and the latter varies with the speed of the motor under test. It is partly for this reason that the direct comparison between the final results of the different methods has been made.

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* Paper by Mr. A. C. W. Vincent Clarke, (see *Journal I.E.E.*, 1940, **86**, p. 597.

INSTITUTION NOTES

THE RECEPTION OF MEMBERS' CHILDREN IN CANADA

The President and Council feel that the members of The Institution would wish to convey to the President of the Canadian Institute of Engineers their high appreciation of the spirit in which Canadian engineers have offered to receive into their homes the children of members of the Institutions of Civil, Mechanical, and Electrical Engineers. The spontaneous nature of this offer, which demonstrates once again the close ties uniting engineers throughout the Empire, renders it all the more regrettable that, owing to the curtailment of the Government scheme, full use is unlikely to be made of the proffered hospitality.

Since the Government's decision was announced a further telegram has been received from the Canadian Institute, extending their original generous offer so that it will also include children privately evacuated to Canada. Members wishing to take advantage of the new offer should communicate with the Secretary of The Institution.

CENTRAL REGISTER OF NATIONAL SERVICE

Following on the voluntary registration of members of the professional Institutions to which reference was made in "Institution Notes" in the July issue of the *Journal*, the Minister of Labour and National Service made an Order, which came into force on the 14th July, requiring all persons enumerated in a Schedule attached to the Order, which includes all professional engineers who had not responded to his appeal (see *Journal I.E.E.*, No. 522, June 1940, page 609, and No. 523, July 1940, page 108) or who are not actually serving with any of the armed forces of the Crown, to enrol their names in the Central Register.

The President and Council desire to thank the very many members of The Institution who returned registration cards prior to the issue of the compulsory Order. Close co-operation will continue to be maintained with the Ministry in the operation of the Register, which is now proving to be a factor of considerable importance in the present national effort.

I.E.E. MODEL FORM OF GENERAL CONDITIONS FOR CONTRACTS

The Council have approved for publication additional clauses for use during the present war with Model Form of General Conditions A (Home—with Erection), revised 1938.

The publication comprises a memorandum and two additional clauses relating to "Price Adjustment" and "Suspension and Termination of the Works" respectively. Copies can be obtained from the Secretary of The Institution or from Messrs. E. and F. N. Spon, Ltd., 57, Haymarket, London, S.W.1, price 6d. each (postage extra).

LONDON STUDENTS' SECTION

Mr. F. Jervis Smith, Associate Member, has been nominated as the representative of the Council on the London Students' Section Committee in place of Mr. G. A. Whipple, who retires from the Council on the 30th September next.

BRITISH STANDARDS INSTITUTION

The I.E.E. Council have nominated Mr. J. R. Beard, M.Sc., Mr. P. V. Hunter, C.B.E., and Mr. W. K. Brasher, B.A., to serve as representatives of The Institution on the Electrical Industry Committee of the British Standards Institution, in place of Mr. E. H. Shaugnessy (resigned), the late Mr. Roger T. Smith, and the late Mr. P. F. Rowell.

SCHOLARSHIPS

The following Scholarships have been awarded for 1940 by the Council:—

Duddell Scholarship (*Annual Value* £150; *tenable for* 3 *years*)

D. La W. W. King (Northampton Polytechnic).

William Beedie Esson Scholarship (*Annual Value* £100, *plus tuition fees*; *tenable for* 2 *years*; *renewable in approved cases for a third year*)

C. H. Bickerdike (London and North Eastern Railway Co.).

David Hughes Scholarship (*Value* £100; *tenable for* 1 *year*).

J. H. Nicoll (Merchant Venturers' Technical College, Bristol).

Salomons Scholarships (*Value* £60 *and* £40 *respectively*; *tenable for* 1 *year*).

H. H. Rosenbrock (University College, London).
P. H. W. Whyman (University College, London).

Thorrowgood Scholarships (*Annual Value* £12 10s. *each*; *tenable for* 2 *years*)

R. J. Post (London Passenger Transport Board).
R. P. Gasson (Southern Railway Co.).

Research Scholarships

It has been agreed that under the present conditions it would be preferable not to award scholarships or to make grants for post-graduate research (Ferranti and Swan Memorial Scholarships and War Thanksgiving Education and Research Fund).

COOPERS HILL WAR MEMORIAL PRIZE AND MEDAL

The Secretary desires to remind members that the latest date for submitting papers in connection with the triennial award of the above Prize and Medal is the 1st October.

The papers may be on any subject coming within the scope of electrical science or electrical engineering and their applications, and must be specially written for the purpose of the competition, which is restricted to Corporate Members of The Institution who were under 35 years of age on the 1st January, 1940.

COUNCIL FOR THE YEAR 1940–1941

No nominations having been received other than those made by the Council (see *Journal* No. 522, June 1940, page 609), those members nominated by the Council are deemed to be duly elected to fill the vacancies that will occur on the 30th September next in the offices of President, Vice-Presidents, Hon. Treasurer and Ordinary Members of Council. The constitution of the Council for the year 1940–1941 will therefore be as follows:—

President.

J. R. Beard, M.Sc.

The Past-Presidents.

Vice-Presidents.

Col. A. S. Angwin, D.S.O., M.C.
P. Dunsheath, O.B.E., M.A., D.Sc.
Major V. Z. de Ferranti, M.C.
Prof. C. L. Fortescue, O.B.E., M.A.

Honorary Treasurer.

E. Leete.

Ordinary Members of Council.

L. G. Brazier, Ph.D., B.Sc.
E. S. Byng.
H. J. Cash.
The Rt. Hon. the Viscount Falmouth.
D. Z. de Ferranti.
P. Good.
H. W. Grimmitt.
Prof. Willis Jackson, D.Sc., D.Phil.
Prof. W. J. John, B.Sc.(Eng.).
Prof. R. O. Kapp, B.Sc.
H. C. Lamb.
A. L. Lunn.
F. Lydall.
E. B. Moullin, M.A., Sc.D.
J. S. Pringle, O.B.E.
F. Jervis Smith.
H. W. Swann.
A. P. Young, O.B.E.

Chairmen and Past-Chairmen of Local Centres.

*T. E. Alger (*Western*).
*J. W. Atkinson, I.S.O. (*North Midland*).
H. R. Beasant (*Western*).
W. A. A. Burgess (*North-Eastern*).
B. A. G. Churcher, M.Sc. (*North-Western*).
*W. J. Cooper (*Scottish*).
W. Dundas (*North Midland*).
*H. Faulkner, B.Sc. (*South Midland*).
*W. Holttum, M.Eng. [*Mersey and North Wales* (*Liverpool*)].
*O. Howarth (*North-Western*).
H. Joseph (*South Midland*).
T. A. McLaughlin, Ph.D., B.E., M.Sc. (*Irish*).
J. E. Nelson [*Mersey and North Wales* (*Liverpool*)].
*J. W. O'Neill (*Irish*).
M. F. Ryan, C.B.E. (*Argentine*).
Prof. S. Parker Smith, D.Sc. (*Scottish*).
*H. G. A. Stedman (*North-Eastern*).
*C. S. Taylor (*China*).
*W. E. Tremain (*Argentine*).
J. Haynes Wilson, M.C. (*China*).

Chairmen of Sections.

H. J. Allcock, M.Sc. (*Transmission*).
C. W. Marshall, B.Sc. (*Meter and Instrument*).
W. J. Picken (*Wireless*).

* Past-Chairman.

METER AND INSTRUMENT SECTION COMMITTEE

No nominations having been received other than those proposed by the Committee, the following is the constitution of the Committee for the year 1940–41:—

Chairman: C. W. Marshall, B.Sc.
Vice-Chairman: W. Phillips.
Immediate Past-Chairman: F. E. J. Ockenden.

Ordinary Members of Committee

A. H. M. Arnold, D.Eng., Ph.D.
A. T. Dover.
D. C. Gall.
L. B. S. Golds.
C. W. Hughes, B.Sc.
A. E. Jepson.
F. J. Lane, M.Sc.
E. H. Miller.
E. W. Moss.
A. G. O'Neill.
W. G. Radley, Ph.D. (Eng.).
S. H. Richards.

Together with the following *ex-officio* members:—

The President.
The Chairman of the Papers Committee.
A representative of the Council.

TRANSMISSION SECTION COMMITTEE

No nominations having been received other than those proposed by the Committee, the following is the constitution of the Committee for the session 1940–41:—

Chairman: H. J. Allcock, M.Sc.
Vice-Chairman: S. W. Melsom.
Immediate Past-Chairman: F. W. Purse.

Ordinary Members of Committee

W. M. Booker.
W. Fennell.
R. E. G. Horley.
J. W. Leach.
J. A. Lee.
W. H. Lythgoe.
E. T. Norris.
J. S. Pickles, B.Sc.Tech.
T. R. Scott, B.Sc.
F. H. Sharpe, B.Sc.
J. A. Sumner.
H. Willott Taylor.

Together with the following *ex-officio* members:—

The President.
The Chairman of the Papers Committee.
J. M. Kennedy, O.B.E. (representing the Council).
P. B. Frost, B.Sc.(Eng.) (representing the Post Office).
H. W. Grimmitt (representing the Electricity Commission).
C. W. Marshall, B.Sc. (representing the Central Electricity Board).

WIRELESS SECTION COMMITTEE

No nominations having been received other than those proposed by the Committee, the following is the constitution of the Committee for the year 1940–41:—

Chairman: W. J. Picken.
Vice-Chairman: T. E. Goldup.
Immediate Past-Chairman: E. B. Moullin, M.A., Sc.D.

Ordinary Members of Committee

A. J. A. Gracie, B.Sc.
L. W. Hayes.
T. H. Kinman.
G. S. C. Lucas.
J. S. McPetrie, D.Sc., Ph.D.
W. L. McPherson, B.Sc. (Eng.).
Col. G. D. Ozanne, M.C.
J. A. Ratcliffe, M.A.
R. P. Ross, B.Sc.(Eng.).
M. G. Scroggie, B.Sc.
R. L. Smith-Rose, D.Sc., Ph.D.
R. T. B. Wynn, M.A.

Representatives of Government Departments

One representative each nominated by the

Admiralty.
Air Ministry.
Post Office.
War Office.

Together with the following *ex-officio* members:—

The President.
The Chairman of the Papers Committee.
A representative of the Council.

WAR EMERGENCY STANDARDS

Organizations are sometimes obliged, on account of urgency due to the war conditions, to seek approval of departures from the requirements of existing British Standard Specifications. Where this problem arises, members are advised to communicate immediately with the British Standards Institution and make use of its War Emergency procedure, which is framed so as to operate with a minimum of delay, for any modification to a B.S. Specification. The War Emergency Standards (or Revisions) are being issued in a distinctive form on yellow paper and apply only to the home market.

BRITISH STANDARDS

The Secretary has been asked by the British Standards Institution to draw attention to the following revised Specification:—

Methods of Testing Fusion Welds, Welded Joints and Weld Metal (Applicable to the Electric Arc Welding of Steel) (B.S. 709).

This British Standard was first issued in November, 1936, but was then confined to the standardization of the bend test as applied to welds and welded joints. Since that date the use of welding in industry has made further strides, and the present revision has been undertaken in order to include standards for other forms of test and to co-ordinate and simplify the various tests already in existence. The advantages resulting from the adoption throughout the industry of similar test-pieces and the same methods of testing so as to enable test data to be readily compared and correlated are obvious. It is hoped, therefore, that the Standard will serve a very useful purpose.

In the Specification a general indication is given of the use to which each of the different tests may be put, but it does not purport to lay down when any particular test should or should not be used on a given structure or what the test results should be. Such requirements are matters to be dealt with in the preparation of each particular Specification in which welding forms a part.

Copies of the revised Specification can be obtained from the B.S.I., price 2s. 3d. each post free.

ASSOCIATE MEMBERSHIP EXAMINATION: MAY, 1940

List of Successful Candidates

(Success in this Examination does not of itself constitute the candidate an Associate Member.)

Parts I and II.*

Arnold, George Frederick.
Betts, Peter Ernest.
Bindoff, Leonard Lewis.
Brassington, Arthur Gerald.
Burns, Rex.
Chambers, Kenneth Douglas.
Chandler, Edward Anthony.
Clotworthy, Neil Desmond.
Cottrell, Seymour.
Davies, Roy Travers.
Dennis, Leslie Arthur.
Dent, Arthur George H.
Drake, Philip John.
Else, William Alan.

Parts I and II—*continued.*

Farrell, Frank Kenneth.
Felgate, Peter Edward.
Field, Peter.
Firth, John Alfred Patrick.
Fletcher, Douglas.
Francis, Edwin John Huntington.
Groom, Alan Robert.
Gutteridge, James Limbird.
Halbe, Dhundiraj Narayan.
Hall, Stanley.
Hart, Henry Edward William.
Hawkes, Edward George.
Haynes, Joseph.
Howard, Richard.
Joice, William Arnold.
Joshi, Vaman Ambadas.
Kasinathan, Natesa.
Kaul, Permashwar Nath.
Lake, Arthur Lawrence.
Langhorne, Thomas Blacklock.
Mankame, Ramnath Yeshwant.
Medlock, Reginald Stuart.
Mills, Victor Ronald.
Newport, Paul Reading.
Newsome, William Antony.
Norman, William John.
Oldham, Hugh William.
Ord, Ian.
Probert, Howard John.
Roberts, John.
Romans, Geoffrey Owen.
Rose, John Cyril.
Sanders, John.
Sutton, Peter.
Tyrrell, Arthur James.
West, Robert Alward.
Wilshaw, Arthur Anthony.
Wilson, Arthur Henry.
Windows, Clifford Edgar.

Part I only

Arrol, Ian.
Dawson, William.
Fowler, Kenneth Thomas.
Johnson, Leonard.
Lawrence, James Scott.
Malhotra, Jamna Das.
Millett, George.
Milne, Frank Alexander.
Rogers, Patrick Sutherland.
Smith, John Keetley.

Part II only

Bailey, Eric Charles.
Brammer, Donald.
Cain, Arthur Leslie.
Davies, Cecil Harold.
Dwelly, John Aldridge.
Feltham, Harold John.
Gale, Donald Henry.
Holmes, Henry Clifford.
Jenkinson, Frank Edward.
Jones, Raymond Lewis.
Jones, Victor George.
Major, William.
Paice, Max Raymond Guest.
Parker, John Reginald.
Payne, Ronald Arthur.
Power, Robert Desmond.
Saunders, Joseph Brown.
Short, Sydney Thomas.
Singh, Pal.
Smelt, Cecil.
Thatcher, Leslie John.
White, Howard Radcliffe.
Wollaston, Francis Butcher.

TRANSFERS

The following transfers were effected by the Council at their meeting held on the 27th June, 1940:—

Student to Graduate

Adams, Edward Francis, B.Sc.(Eng.).
Bulford, Frank Frederick.
Cosgrave, Stanford Thomas.
Davis, Patrick Goronwy, B.Sc.(Eng.).
Deshpande, Prabhakar.
Drake, John Barnard.
Gladwin, Arthur Sullivan, B.Sc.
Hurford, Denis George, B.Sc.(Eng.).
Jeans, Gerald Leslie G., B.Sc.(Eng.).
Kinra, B. R., B.Sc.(Eng.).
Lee, Joseph, B.Sc.
Roberts, Frederic Francis, B.Sc.(Eng.).
Singh, Bansh Raj.
Tokmakoff, Wladimir Veniamin.
van Rooyen, Lionel Jacques B.Sc.(Eng.).

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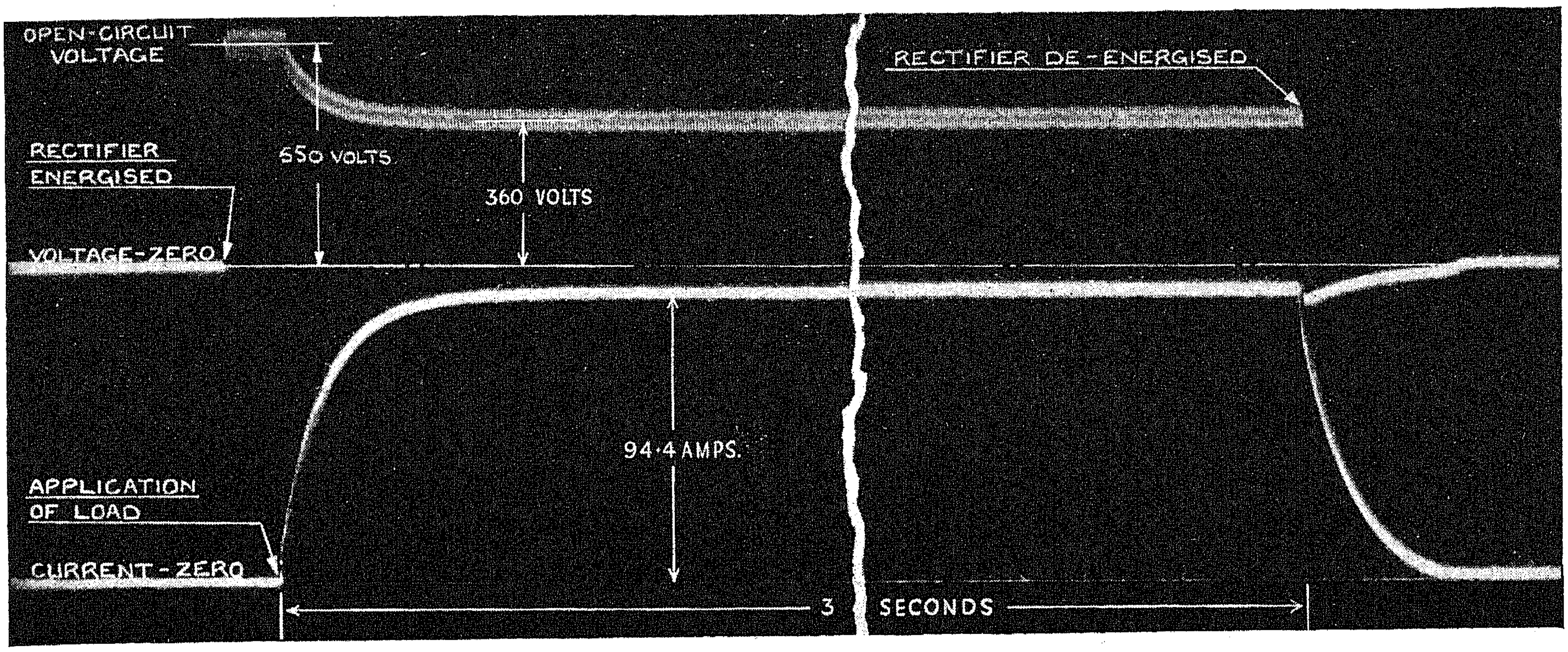
* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

SELENIUM RECTIFIERS IN SERVICE

No. 8



OPERATION OF LARGE CIRCUIT BREAKERS

AN application of the *Standard* Selenium Rectifier which is of great practical importance is the operation of circuit-breaker closing mechanism from A.C. supplies. As is well known, A.C. solenoids are unsatisfactory in comparison with D.C. solenoids for closing circuit-breakers and the use of an A.C. operating motor does not, in general, give the rapid closing action required by modern switchgear practice.

The most satisfactory apparatus for converting the A.C. supply to a direct current for this purpose is the *Standard* Selenium switch-closing Rectifier. The electrical characteristics of a Selenium Rectifier suitable for circuit-breaker operation are illustrated by the oscillogram above which shows the voltage across and the current obtained on an inductive load which, in this instance, consisted of a coil such as is used for solenoid operating mechanisms.

This oscillogram was taken during tests made to determine the suitability of the *Standard* Selenium Rectifier for circuit-breaker closing duty.

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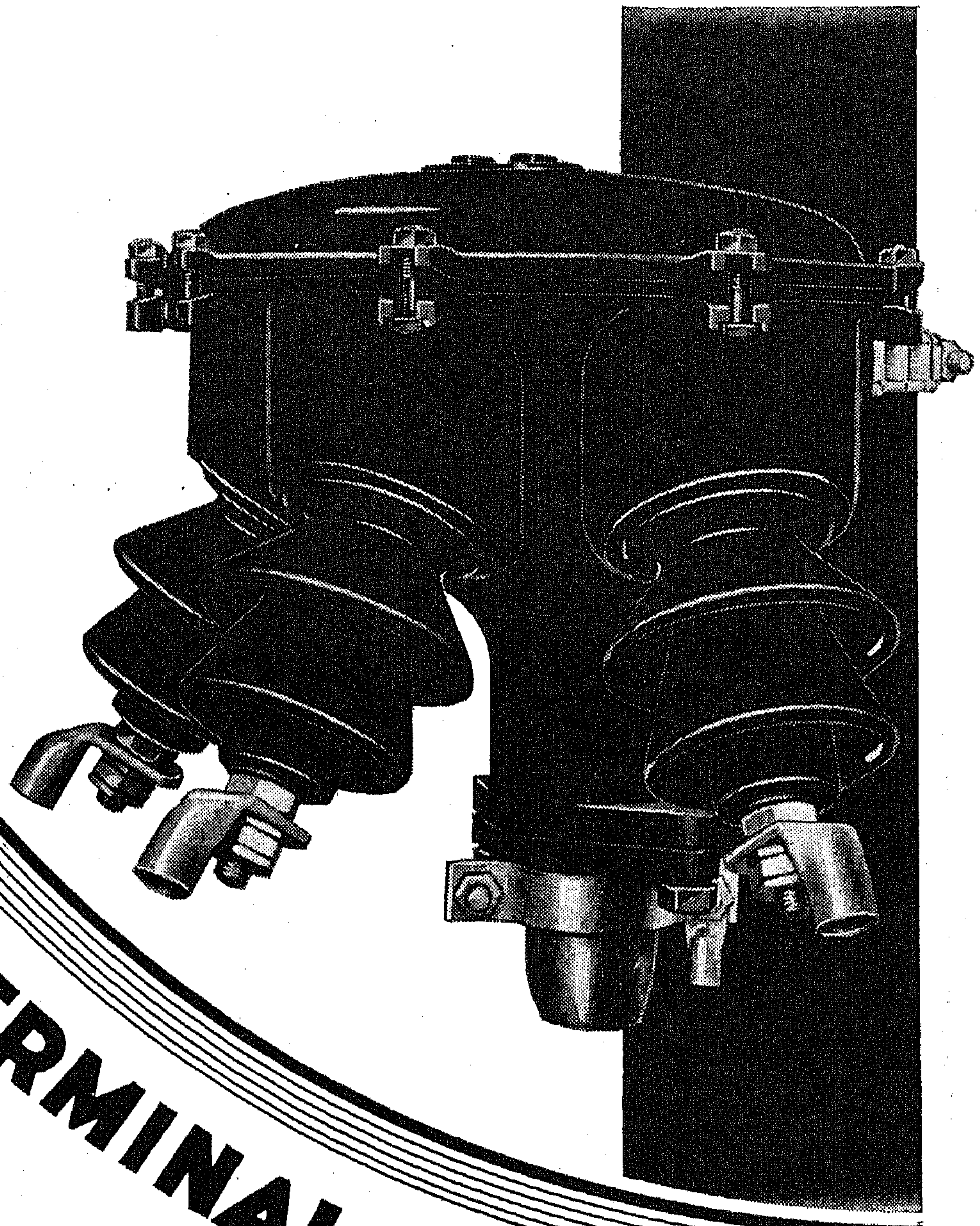

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Working Pressure — Unearthed	—		3·3 kV.		6·6 kV.		11 kV.	
Sectional Area of Conductors	·12 □″	·30 □″	·12 □″	·30 □″	·12 □″	·30 □″	·12 □″	·30 □″
List Numbers ...	A 2988	A 2990	A 2989 A 2992	A 2991 A 2994	A 2993 A 2996	A 2995 A 2998	A 2997	A 2999
Dry Test (1 min.) kV. to Earth	22·0	30·0	35·0	40·0	45·0	45·0	55·0	55·0
Flashover—Dry kV. to Earth	30·0	38·0	36·0	43·0	48·0	49·0	57·0	80·0
Wet Test (½ min.) kV. to Earth	22·0	30·0	30·0	40·0	40·0	40·0	50·0	55·0
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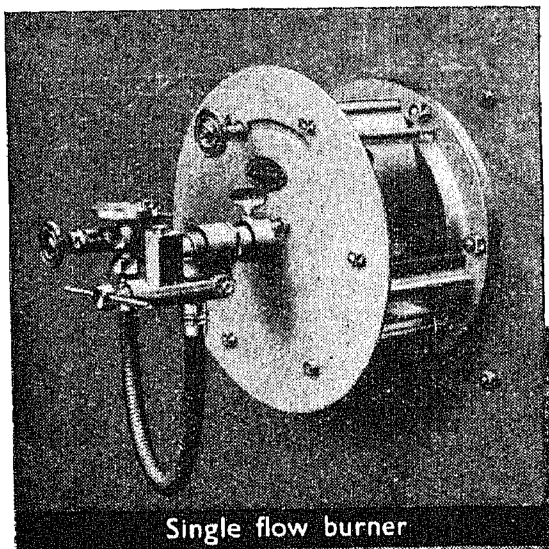
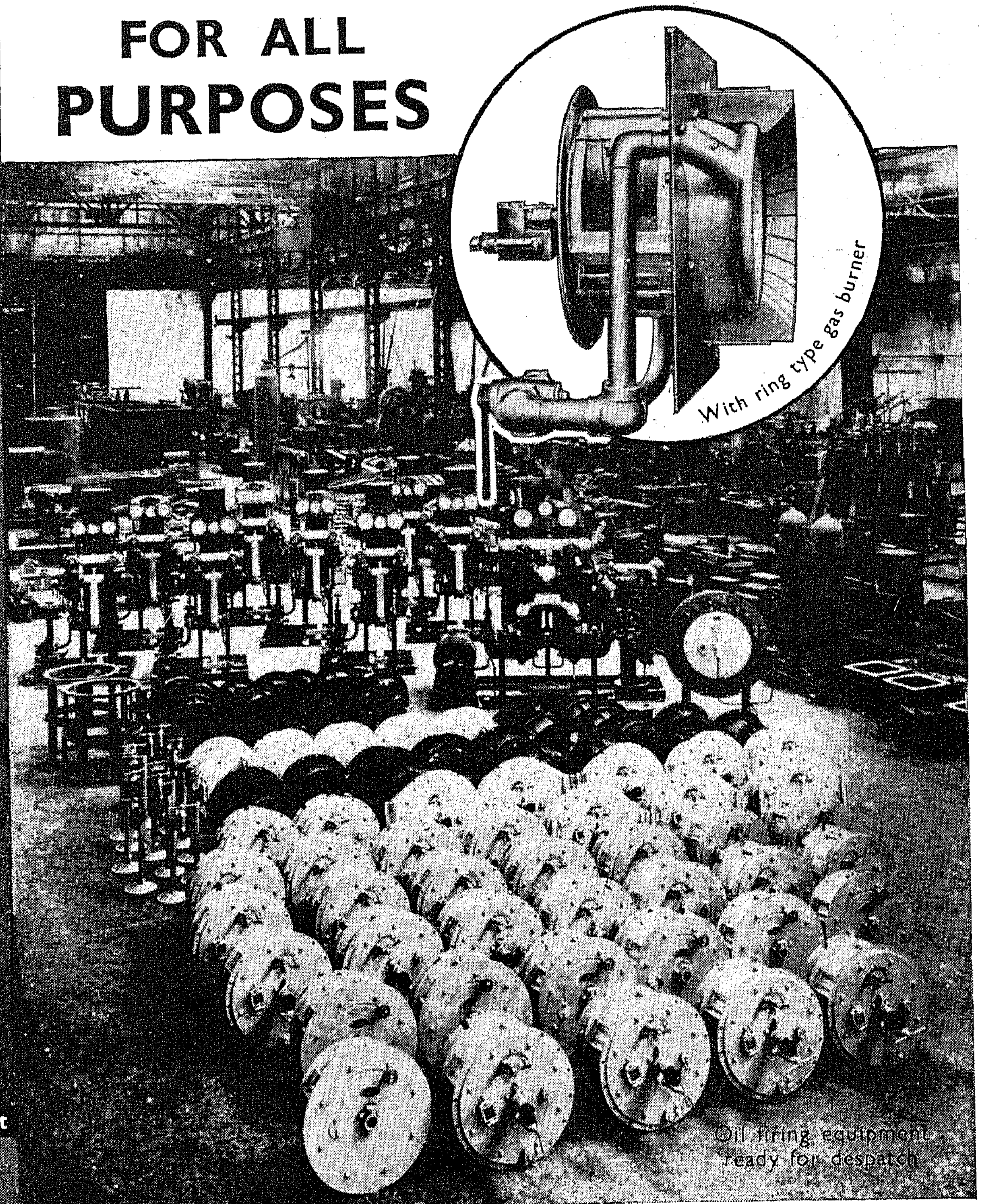
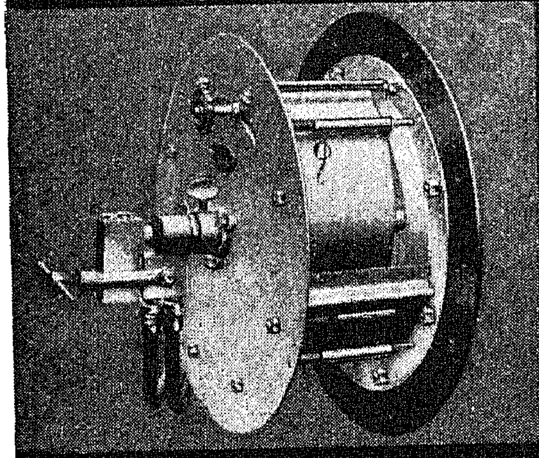


Single flow burner

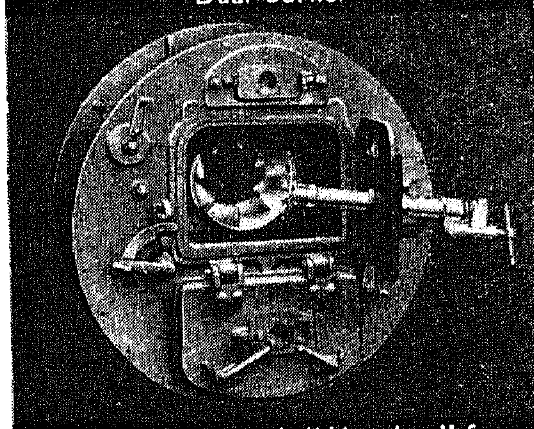


With ring type gas burner

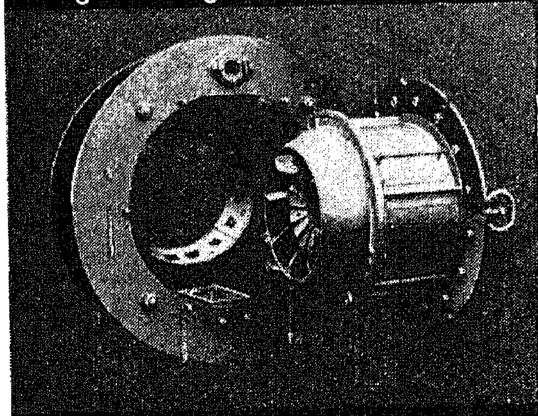
Oil firing equipment ready for despatch



Dual burner



Overgrate firing with "Howden" front



Double front register—hinged

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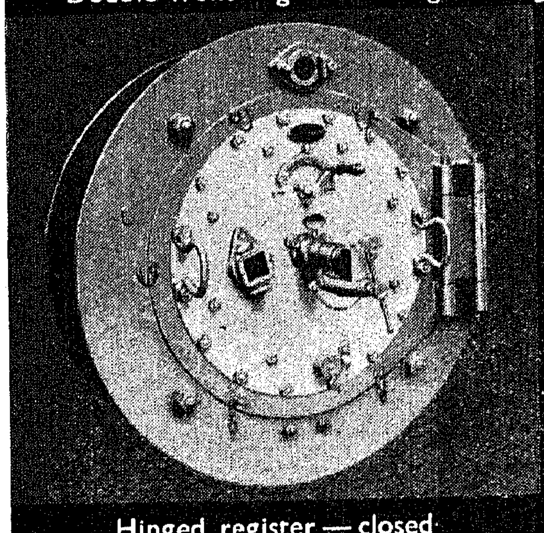
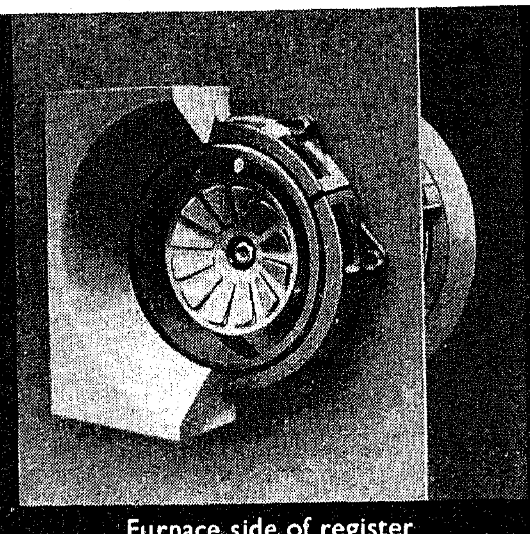
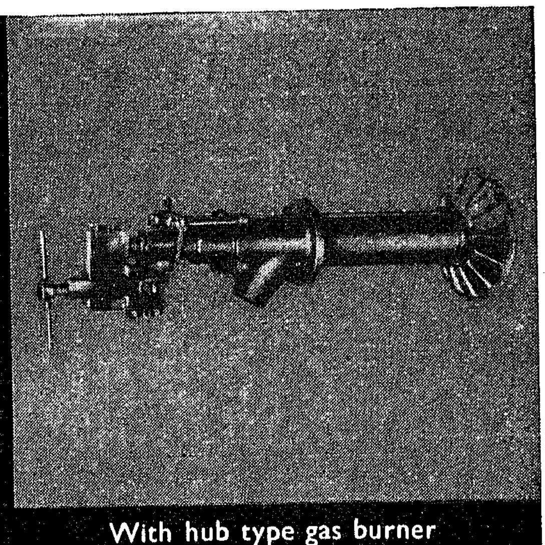


Hinged register — closed



Furnace side of register



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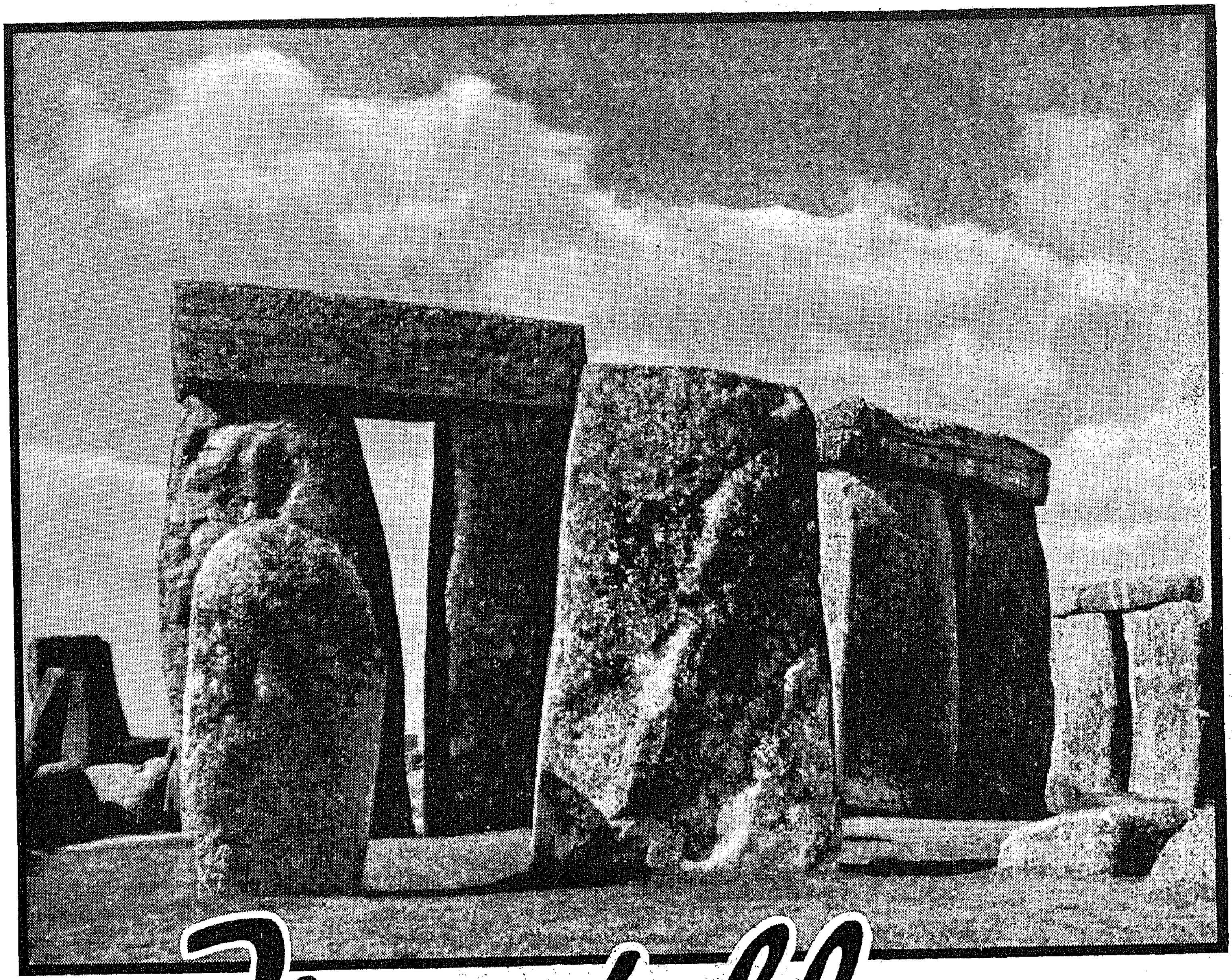

Time tells......

OF the age and origin of Stonehenge, little or nothing is really known; but, in all probability, it was erected at some period in the Bronze Age. Some of the stones were almost certainly brought from Pembrokeshire, and imagination staggers at the enormous labour and determination involved in their transport all this distance. Time alone has proved their dependability and the skill employed in the design and erection of this great monument. A more modern example of a product proving its inherent durability, is that provided by the Westinghouse Metal Rectifier, which has already withstood the severe test of time by proving itself absolutely reliable under all conditions of service, and justified its choice for such purposes as battery charging, electro-deposition, electrostatic precipitation, etc.

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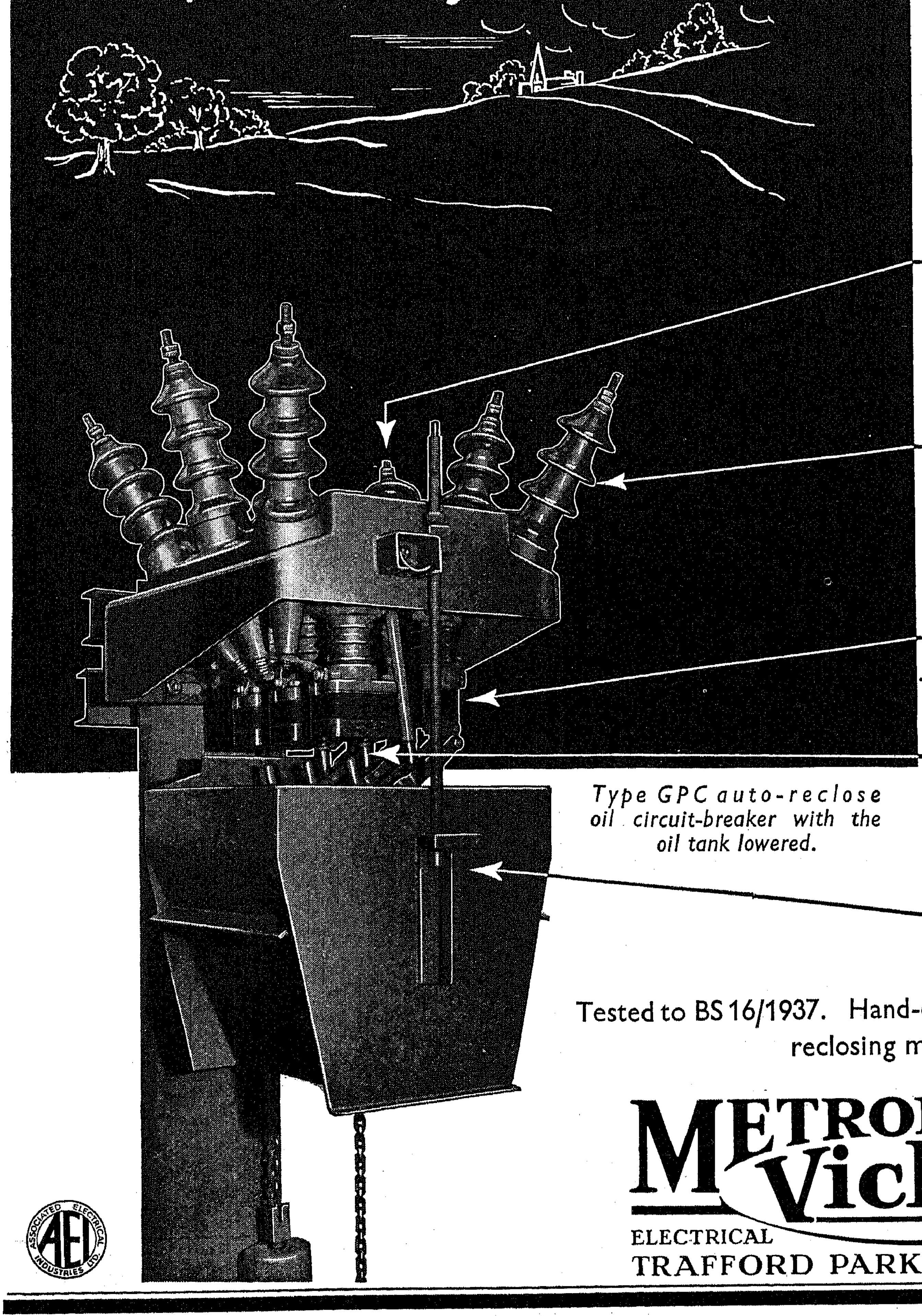

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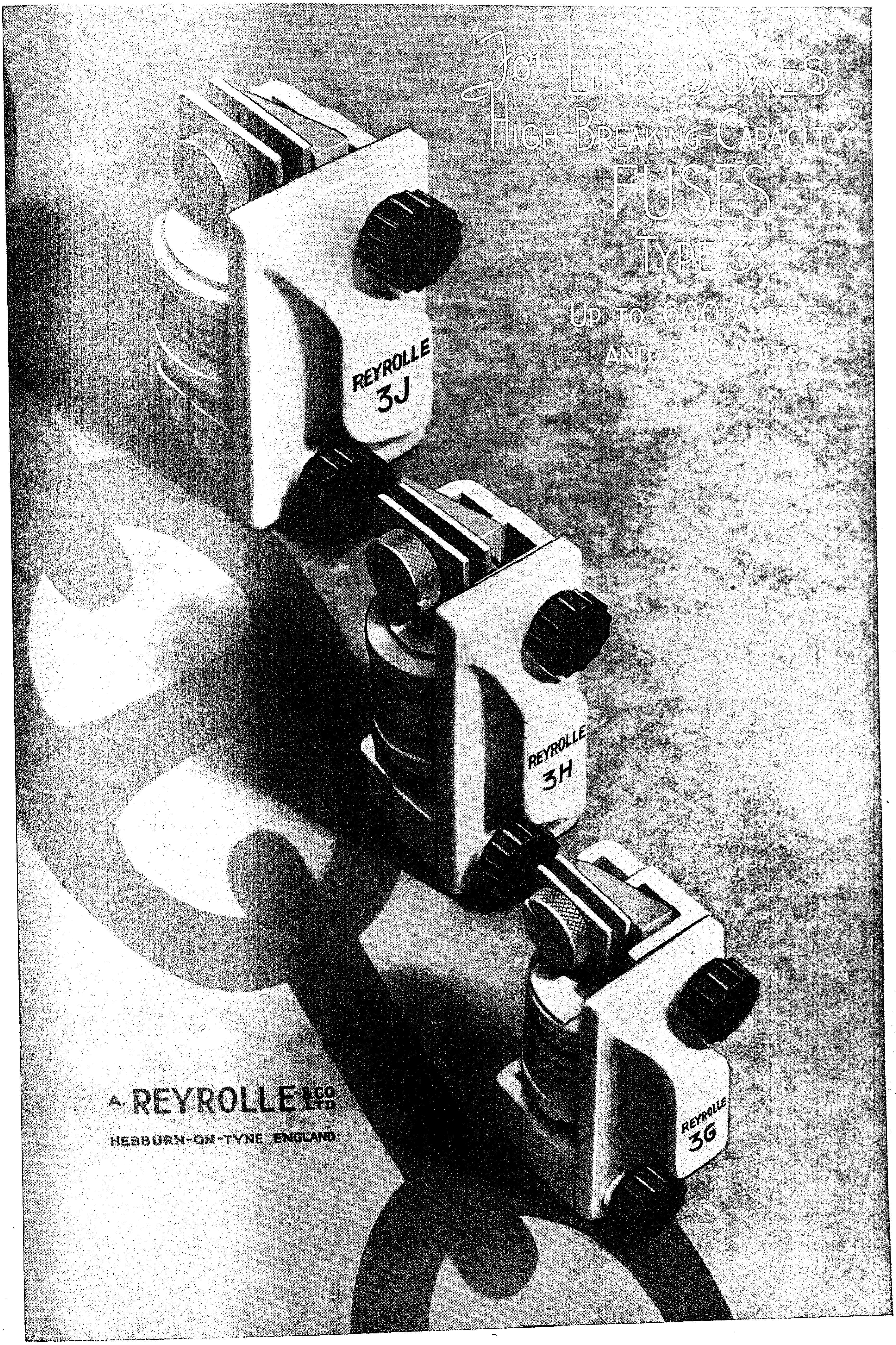

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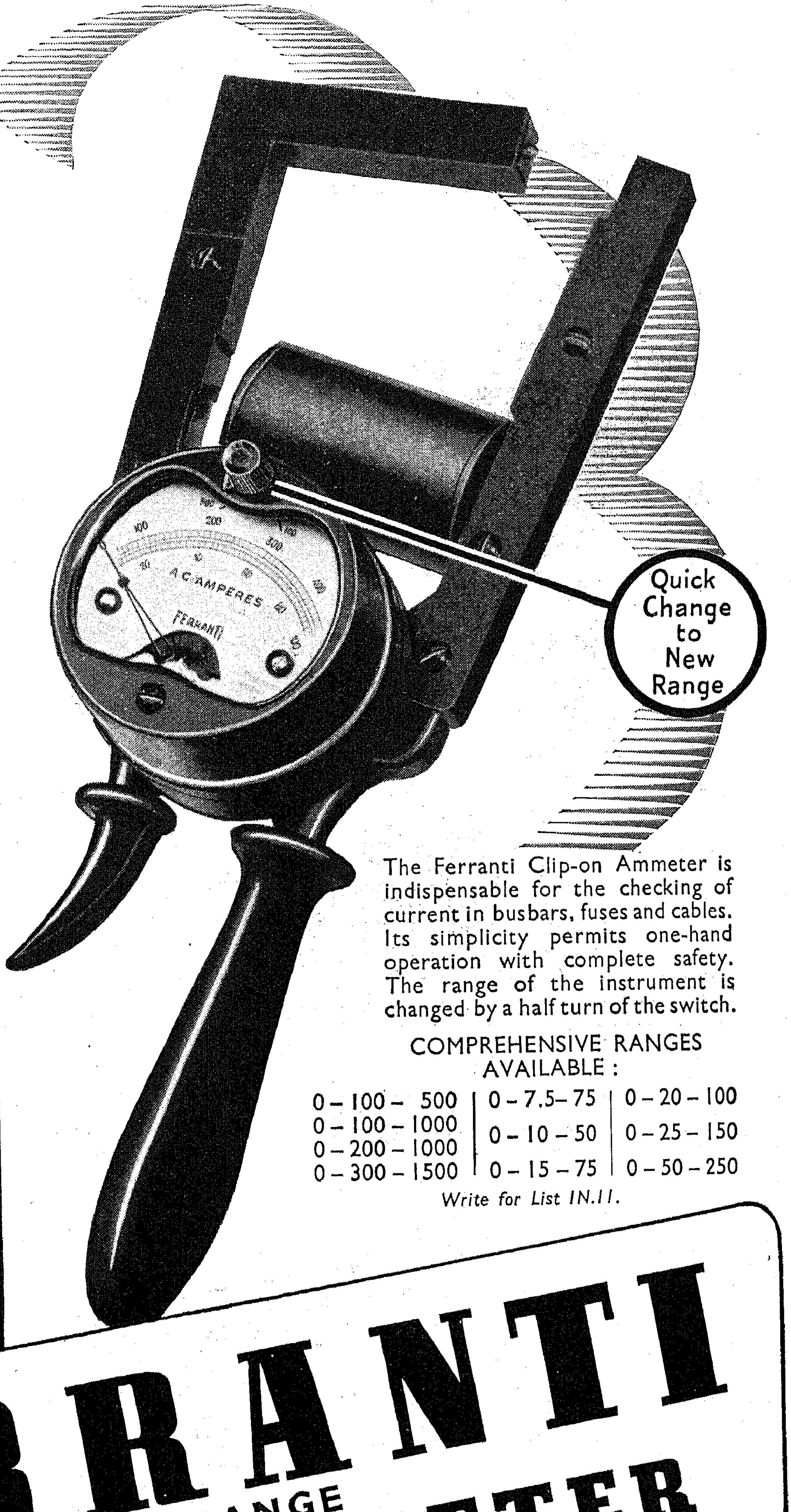

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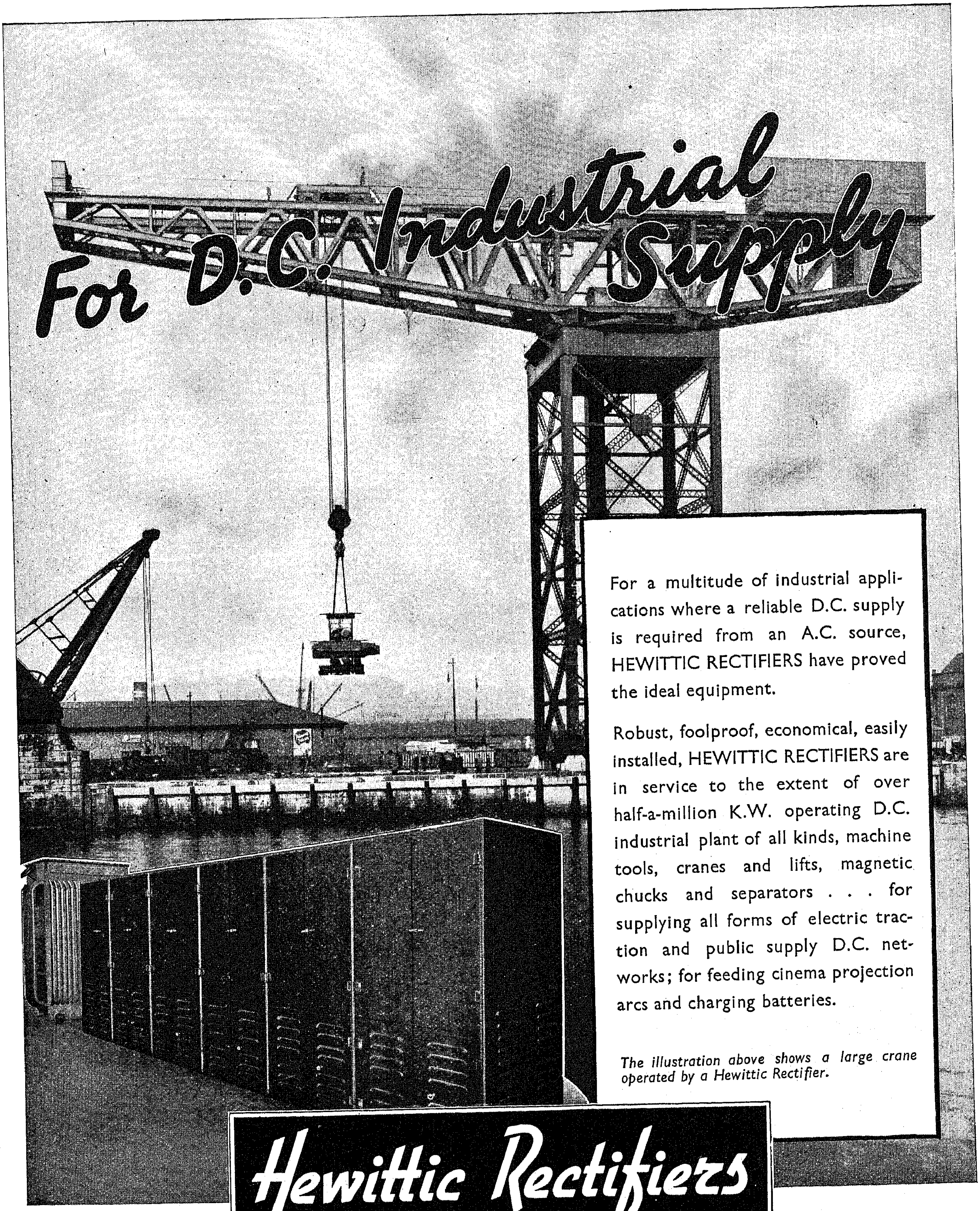

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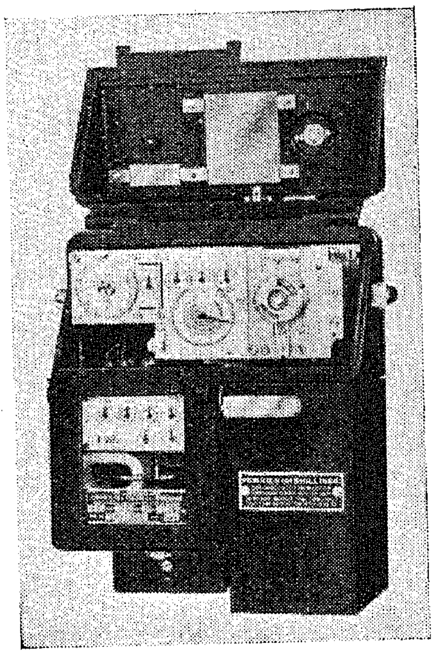

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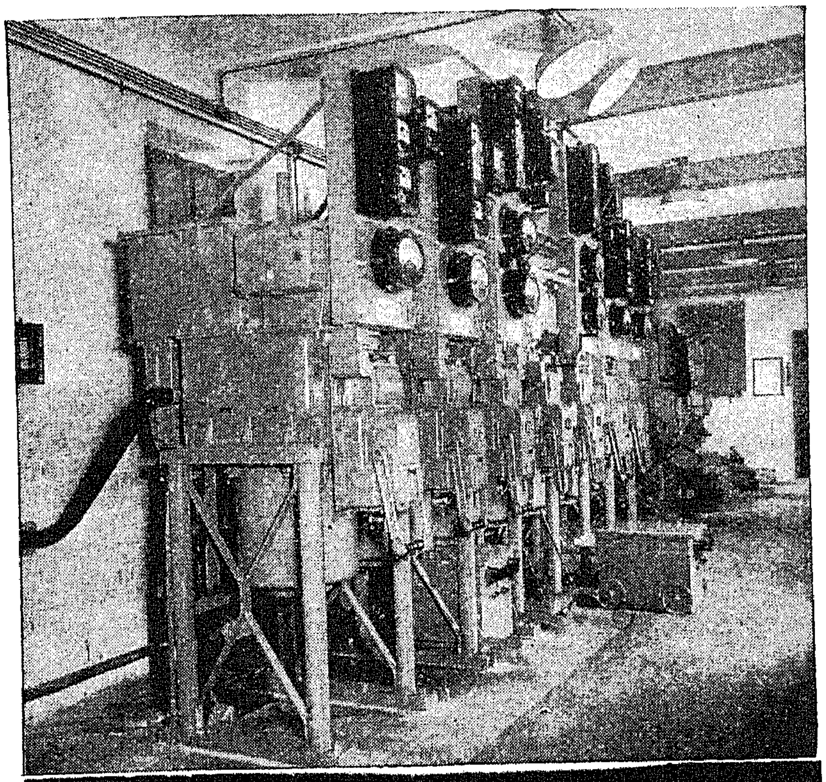

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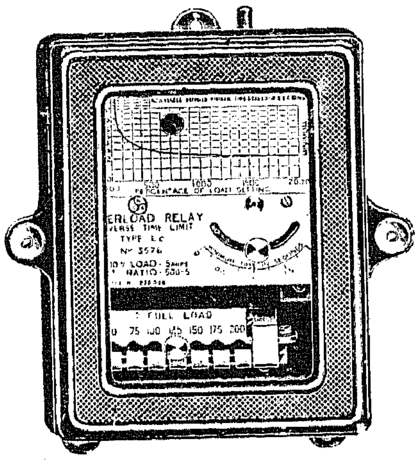

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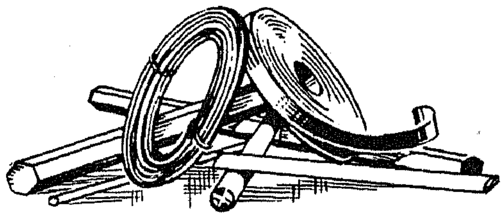

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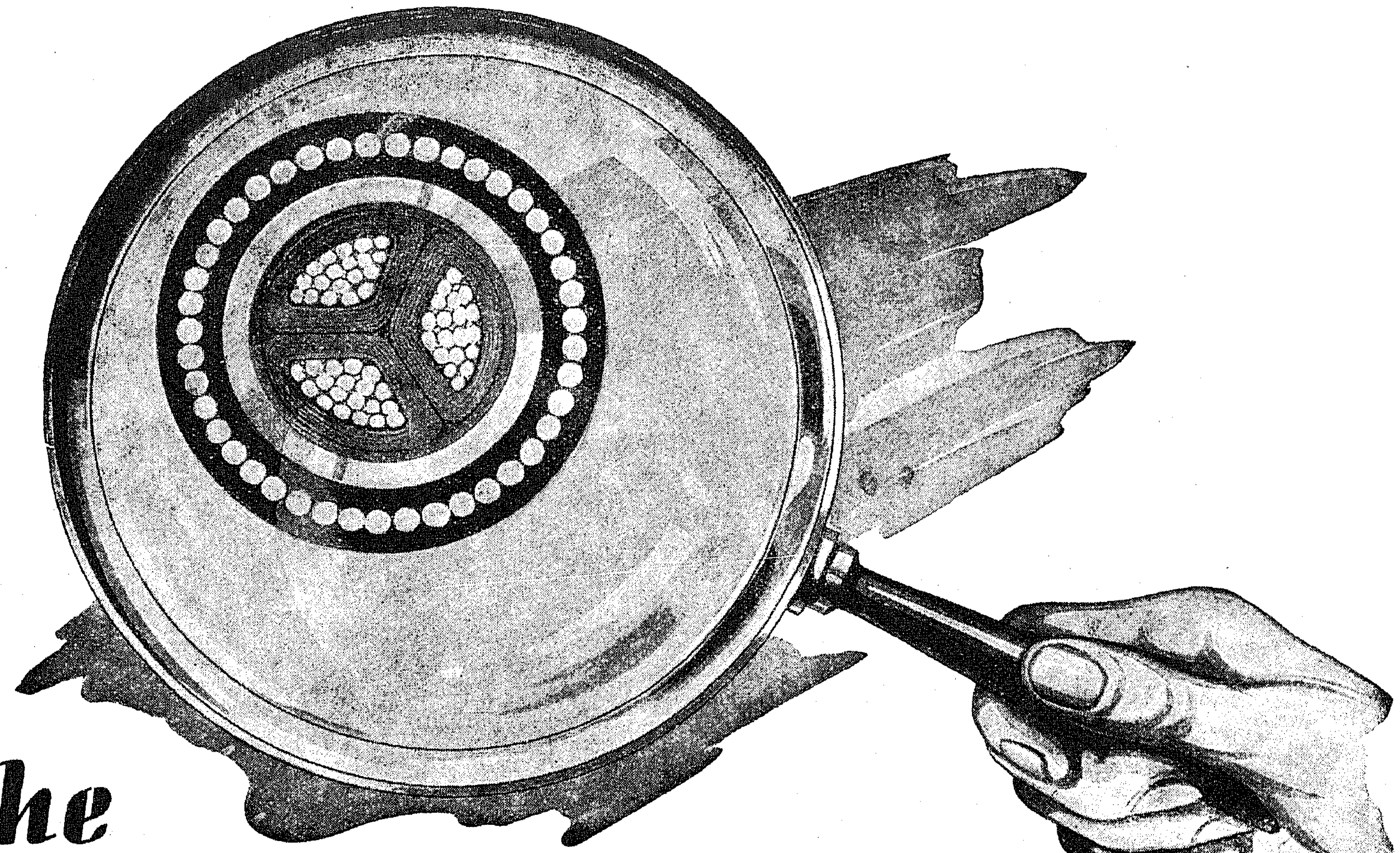

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